Strangeness Report

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Contents

→ I concentrate on strange particle abundances (yields and ratios)

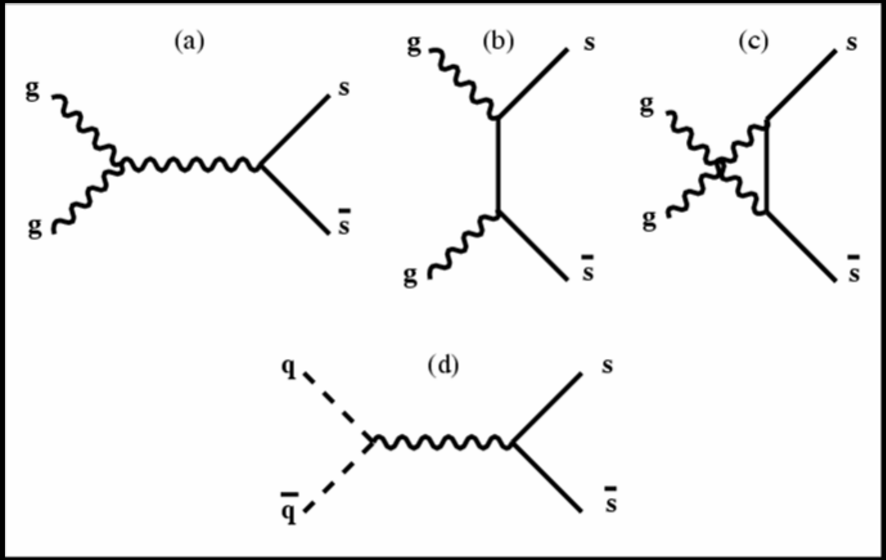
- QGP predictions
- Enhancement pattern
- Hadronic transport
- Thermal models
- Beyond equilibrium?
- The Φ
- Extras
- Conclusions

not covered: Resonances (Fachini), Spectra (Velkovska), Flow (Retiere), Pentaquarks (Jaffe), HBT (Magestro)

Two historic QGP predictions

- restoration of χ symmetry -> increased production of s
  - mass of strange quark in QGP expected to go back to current value
    - m_S ~ 150 MeV ~ Tc
  - → copious production of $s\bar{s}$ pairs, mostly by gg fusion

[Rafelski: Phys. Rep. 88 (1982) 331]
[Rafelski-Müller: P. R. Lett. 48 (1982) 1066]

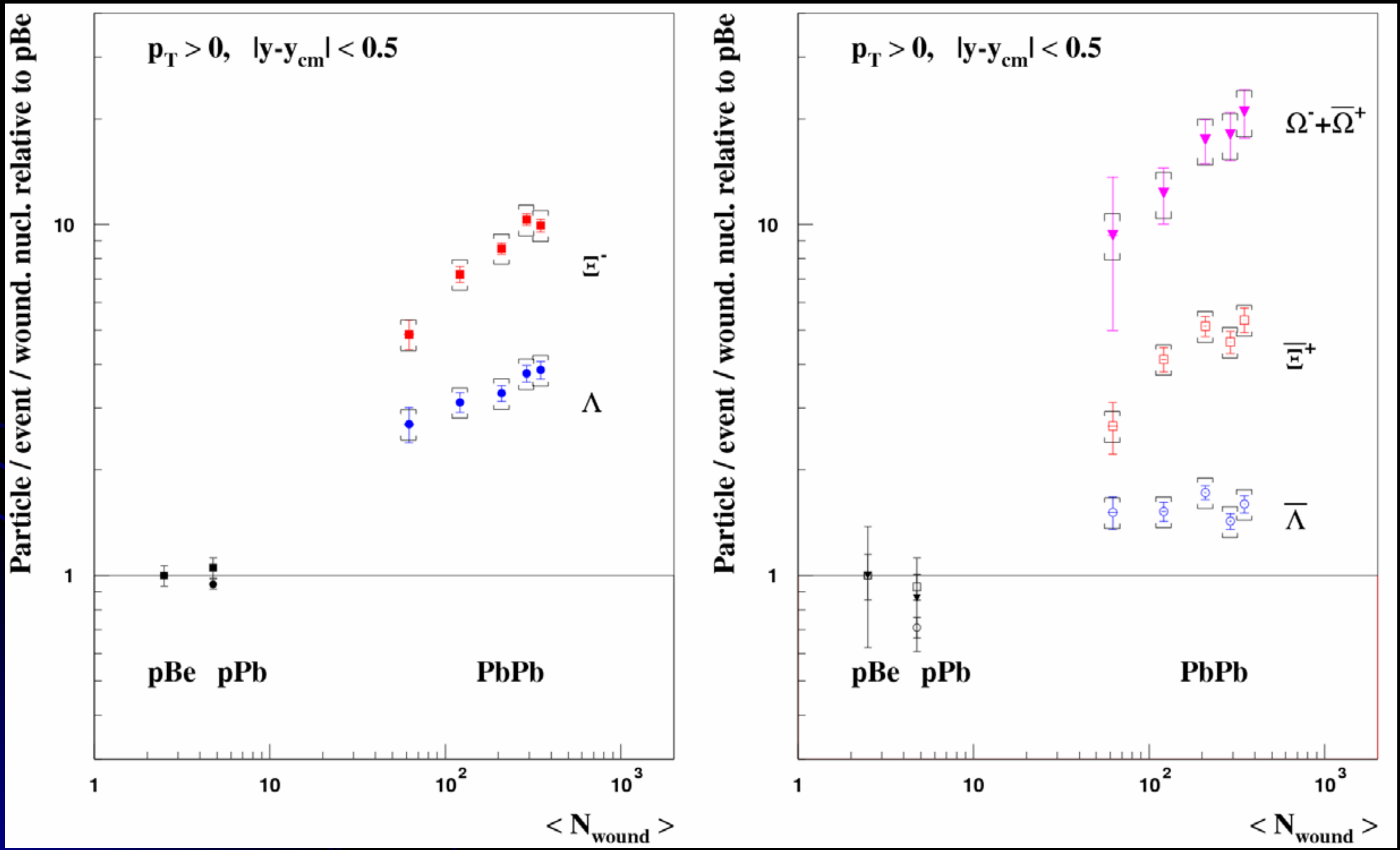


- deconfinement → stronger effect for multi-strange
  - can be built using uncorrelated s quarks produced in independent microscopic reactions
  - → strangeness enhancement increasing with strangeness content

[Koch, Müller & Rafelski: Phys. Rep. 142 (1986) 167]

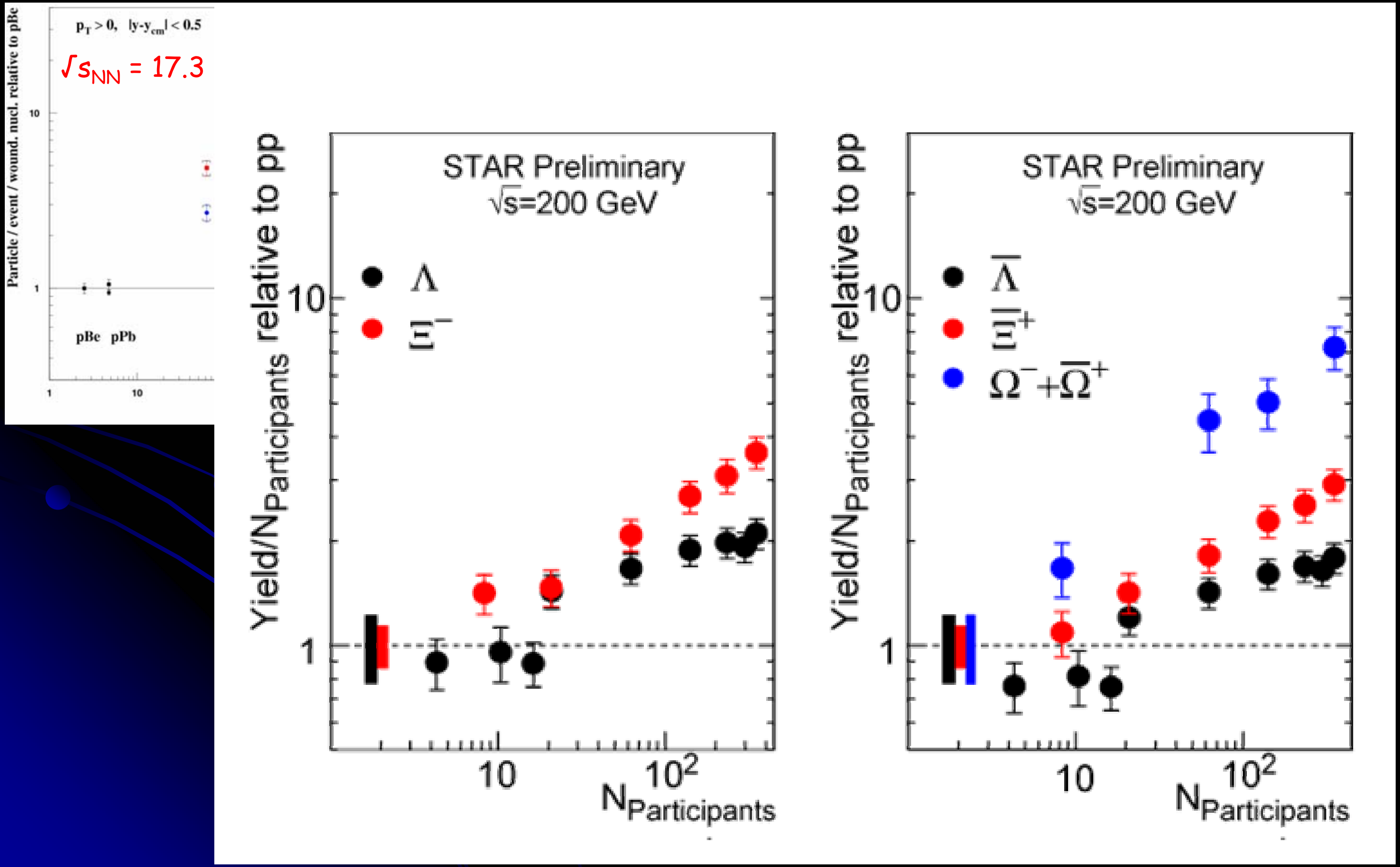
and indeed…

- @ top SPS (NA57, $\sqrt{s_{NN}}$ = 17.3 GeV)



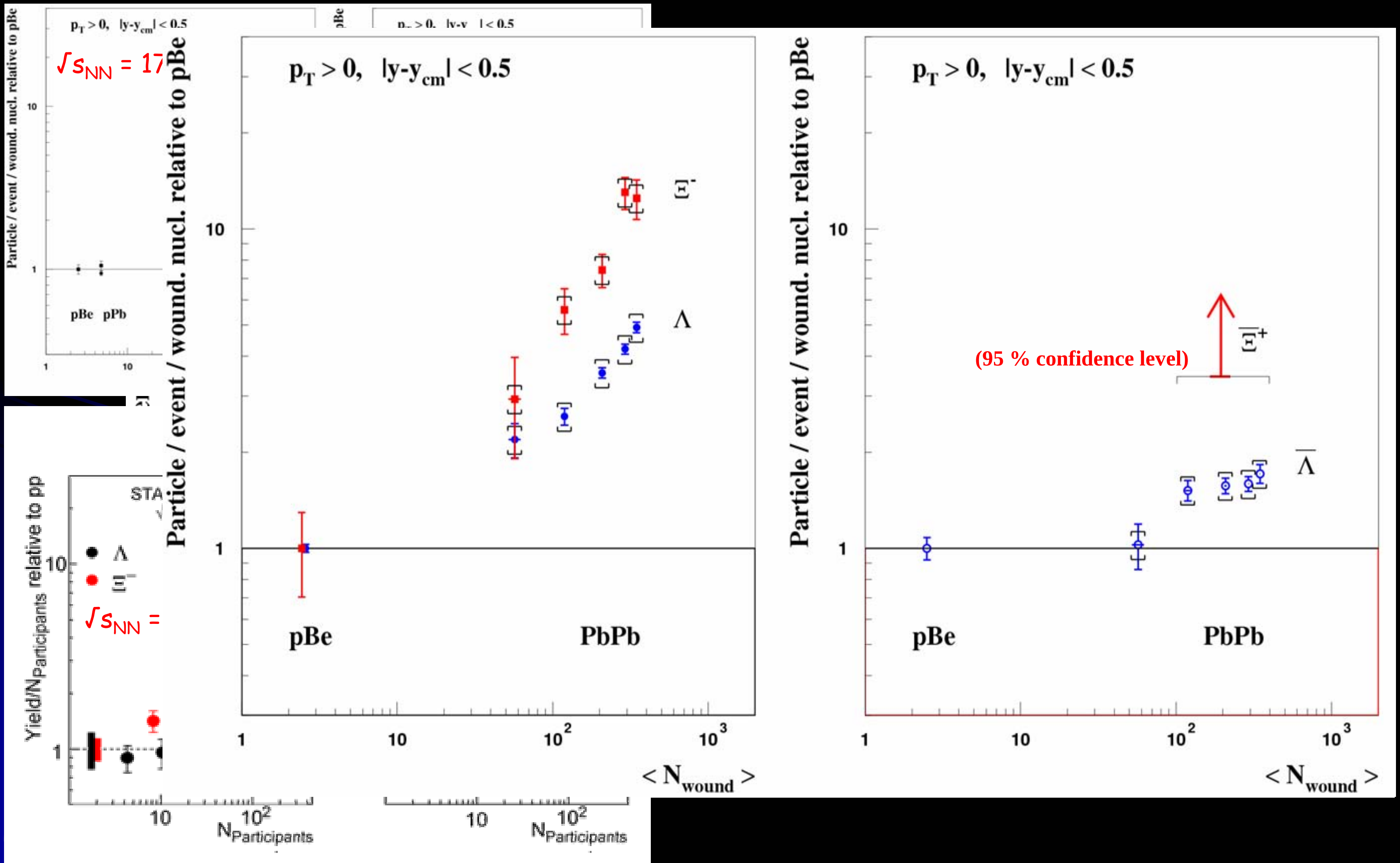
and indeed…

- and (yesterday's news) @ RHIC (STAR, $\sqrt{s_{NN}}$ = 200 GeV)



and indeed…

- and (yesterday's news) @ low E SPS (NA57, $\sqrt{s_{NN}}$ = 8.8 GeV)



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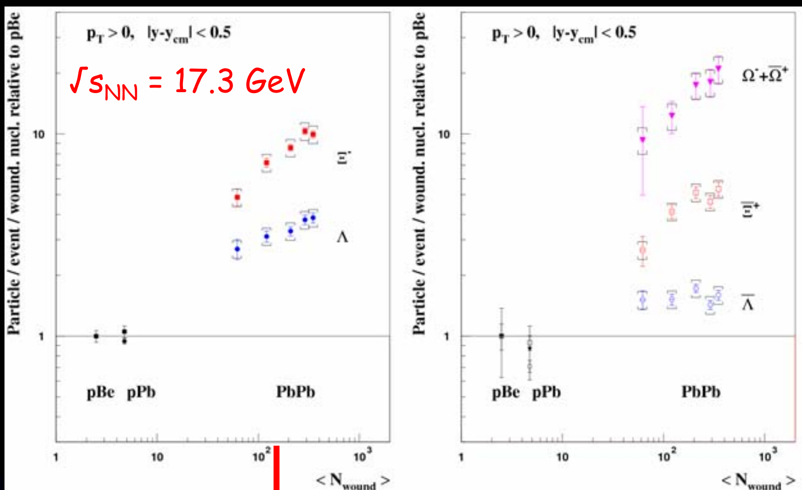

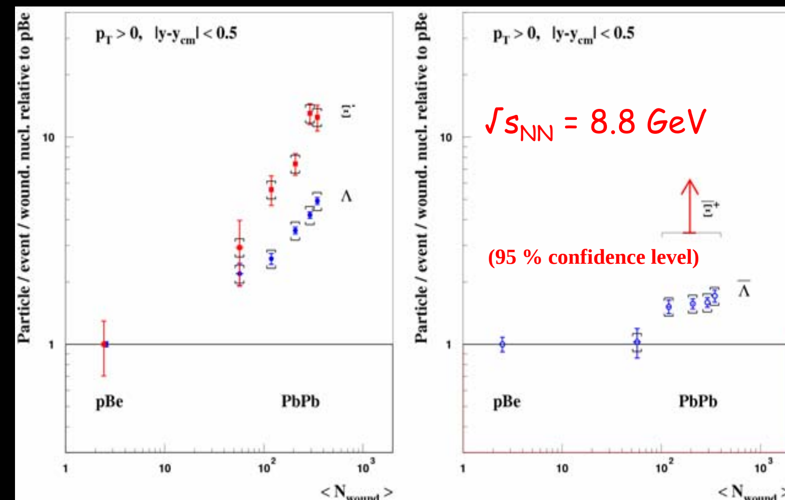

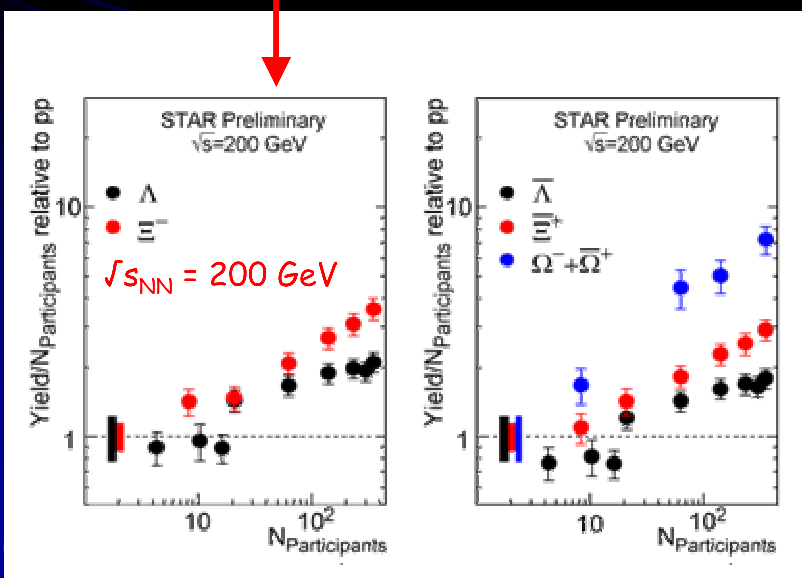

- qualitatively similar picture emerging from 8.8 to 200 GeV

Alternative definition of pA enhancement?

e.g.: [Fischer: Nucl. Phys. A 715 (2003) 118]

- two-component model of particle production:

  → in pA: $Y_{pA} = [\nu/2 + 1/2]\, Y_{pp}$ (ν = number of collisions)

  $= N_{part}\, Y_{pp}/2$

- enhancement "blamed" on projectile component only:

<u>usual enhancement</u>: E

$(Y/N_{part})_{pA} = E \cdot (Y/N_{part})_{pp}$

→ $Y_{pA} = E\, [\nu/2 + 1/2]\, Y_{pp}$

<u>alternative enhancement</u>: F

$Y_{pA} = [\nu/2 + F/2]\, Y_{pp}$

reasonable for baryon number transfer, but do e.g. strange quarks know if they come from projectile or target ?

- then: $(F - 1) = (E - 1)\, N_{part}$

  → enhancement within pA appears even if pA yields $\propto N_{part}$

Hadronic transport

- Hadronic transport codes:
  - do reasonably well on singly strange particles
  - but fail to reproduce the production of multi-strange particles at SPS and RHIC
    - see for instance:
      - [Soff et al.: Phys. Lett. B471 (1999) 89],
      - [C.Greiner: nucl-th/0208080 and references there],
      - [STAR: nucl-ex/0307024],
      - [Huovinen & Kapusta: nucl-th/0310051]

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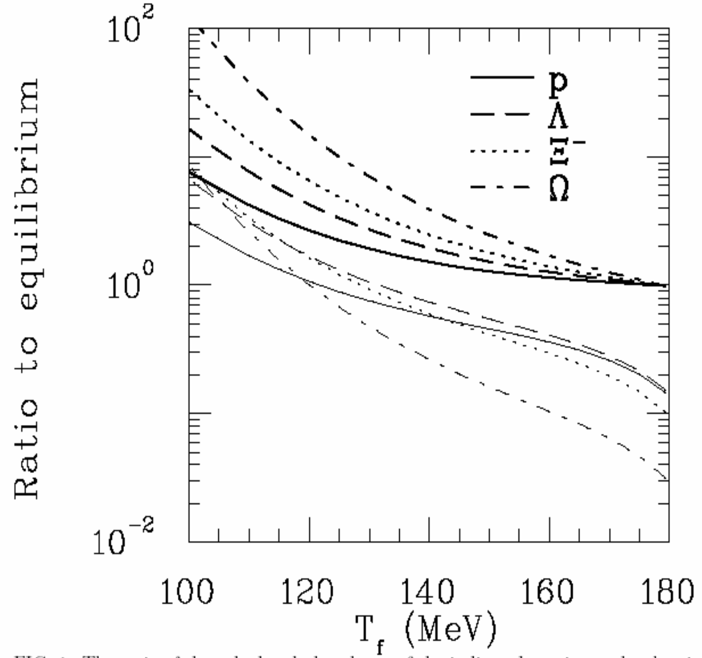

FIG. 1. The ratio of the calculated abundance of the indicated species to the chemical equilibrium value as a function of the local temperature. The upper set of curves start with the baryons in equilibrium at T_c, the lower set start with no baryons.

[Huovinen & Kapusta: nucl-th/0310051]

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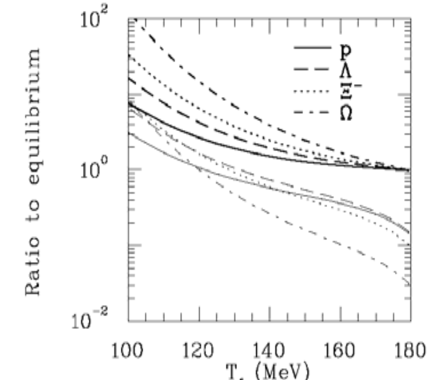

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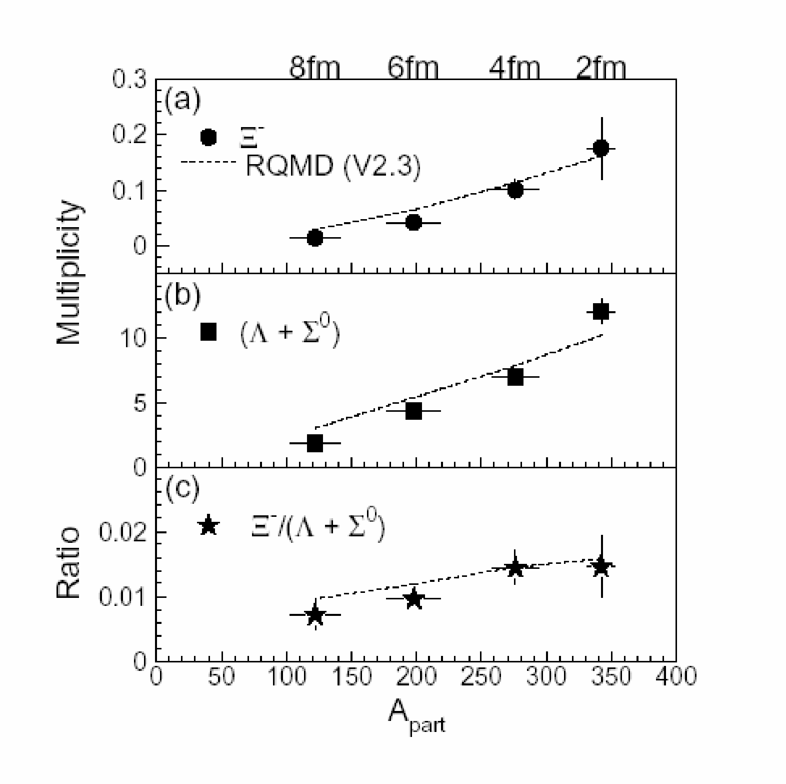
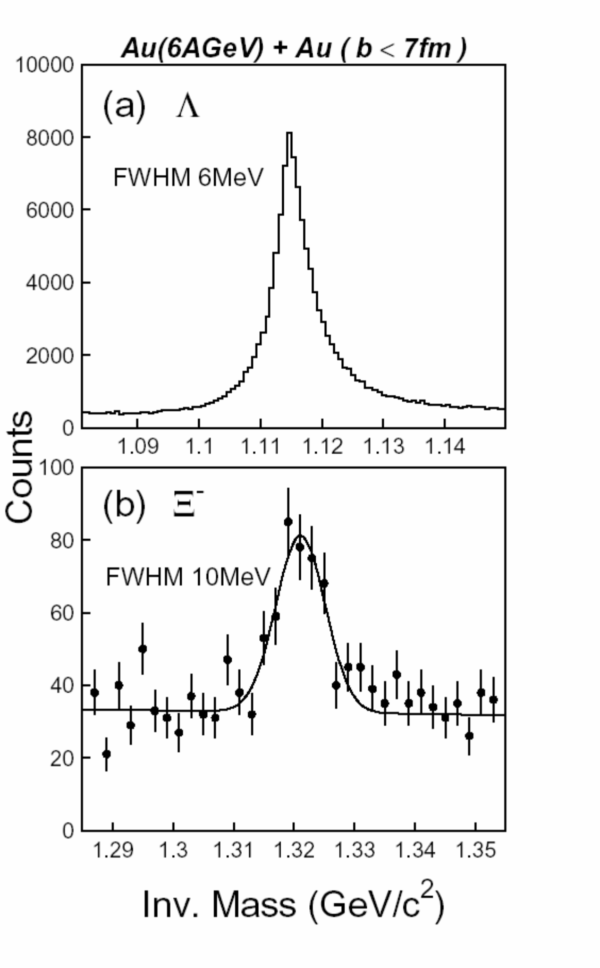
[Huovinen & Kapusta: nucl-th/0310051]

  - they get closer if:
    - masses are reduced towards chiral values
      or string tension is enhanced with respect to ee/pp/pA
    - enhanced contribution from inelastic scattering during expansion
- Activity is still ongoing:
  - e.g.: [Capella: nucl-th/0303045; Subrata Pal et al.: nucl-th/0106074]
  - hadronic models are getting more and more exotic...

Meanwhile at the AGS…

- Nice new measurement: Ξ^- production close to threshold, Au-Au @ 6 A GeV (E895) [P.Chung et al.: nucl-ex/0302021]
- At this energy RQMD works fine!





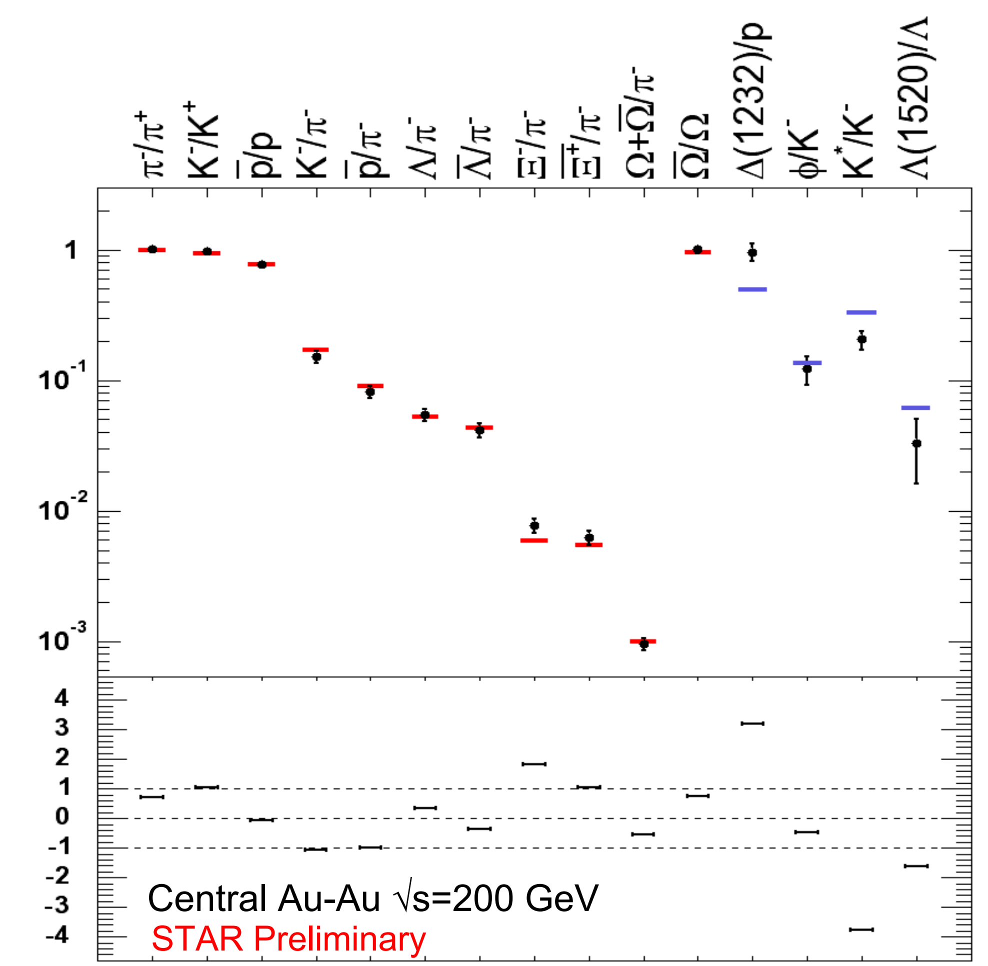
Thermal fits

- Thermal fits don't do too bad!

e.g.: brand new @ RHIC 200

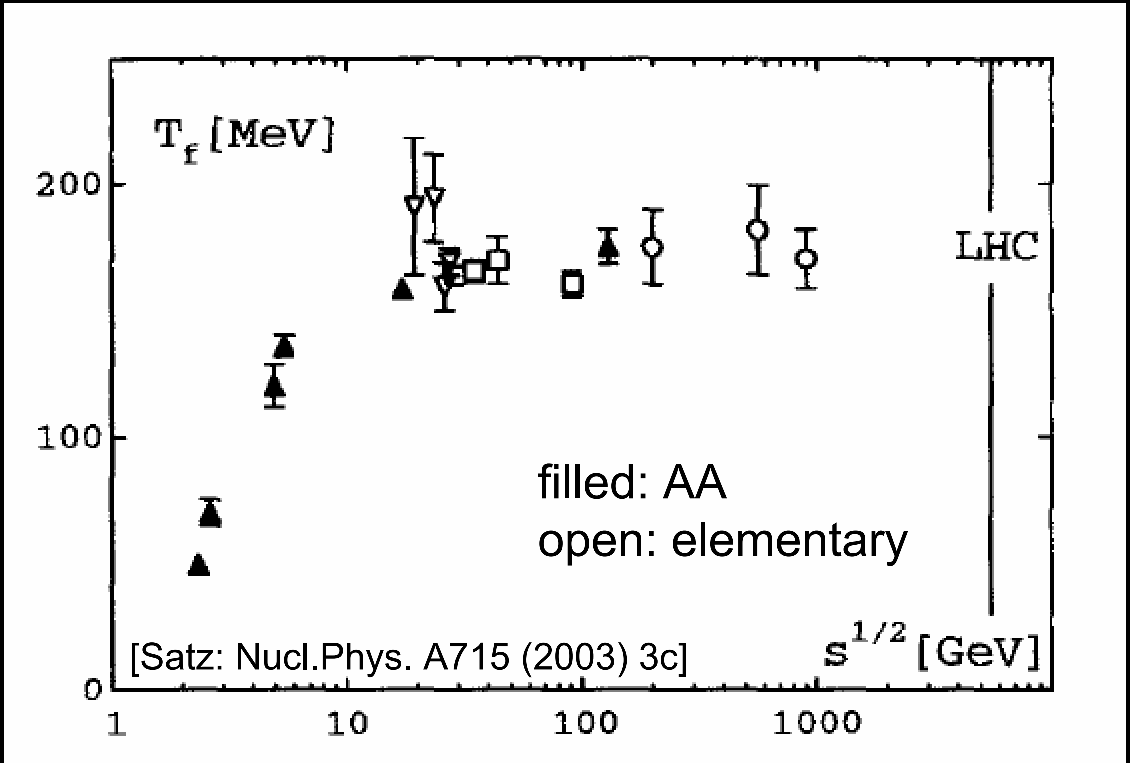
- T_{ch} = 160 ± 10 MeV
- μ_B = 24 ± 5 MeV

(STAR Preliminary)



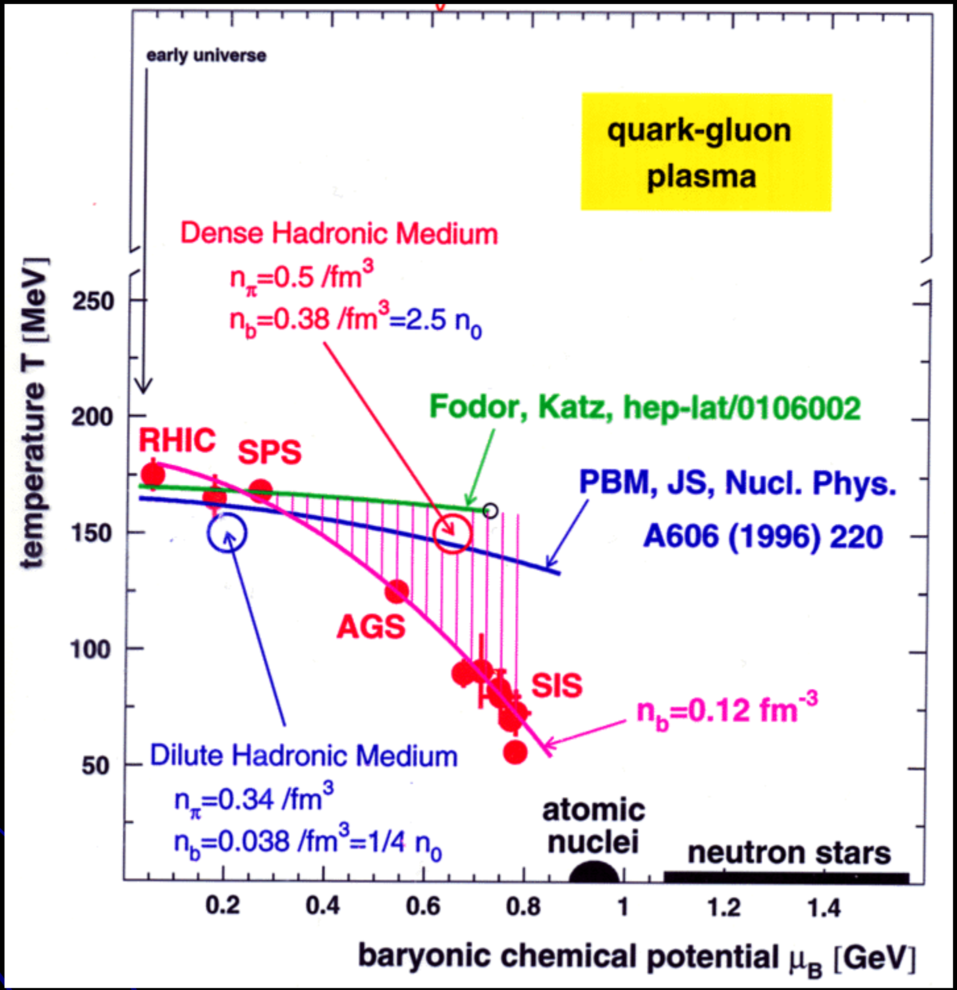
- relative particle abundances ~ as expected at thermodynamical equilibrium for grand-canonical system, <u>even for rare, multi-strange particles</u>

T systematics



- it looks like Hagedorn was right!
  - if the resonance mass spectrum grows exponentially (and this seems to be the case), there is a maximum possible temperature for a system of hadrons
  - indeed, we don't seem to be able to get a system of hadrons with a temperature beyond T_{max} ~ 170 MeV!

T vs μ_B systematics



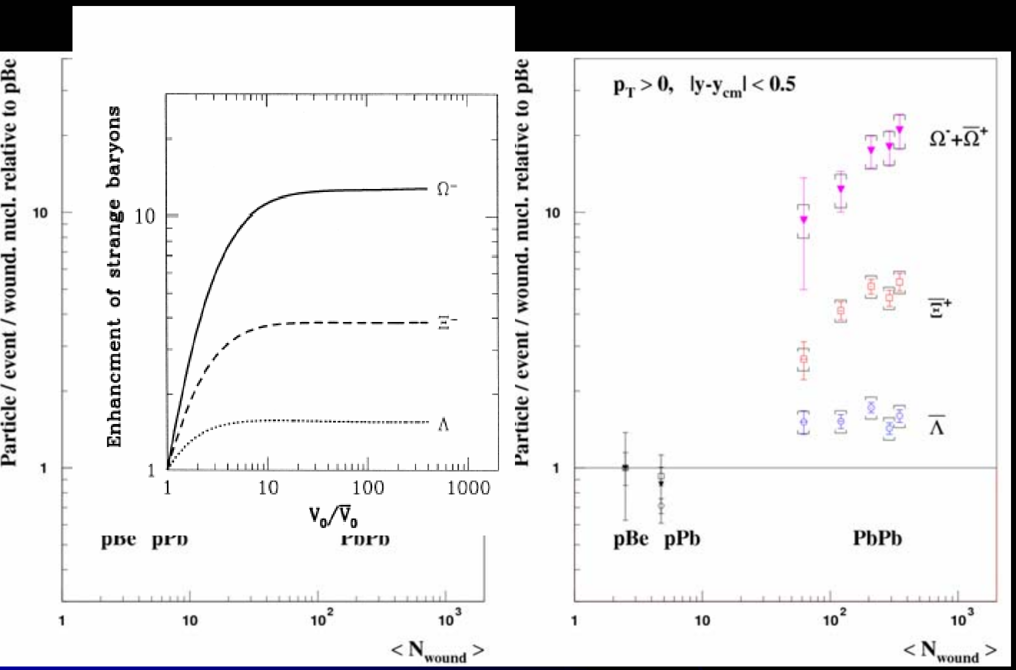
- the extracted freeze-out points at SPS and RHIC lay very close to the predicted QGP phase boundary

Canonical vs Grand Canonical

- Energy penalty to create a strange particle:
  - Canonical:

    computed taking into account also energy to create companion to ensure conservation of strangeness
  - Grand Canonical limit:

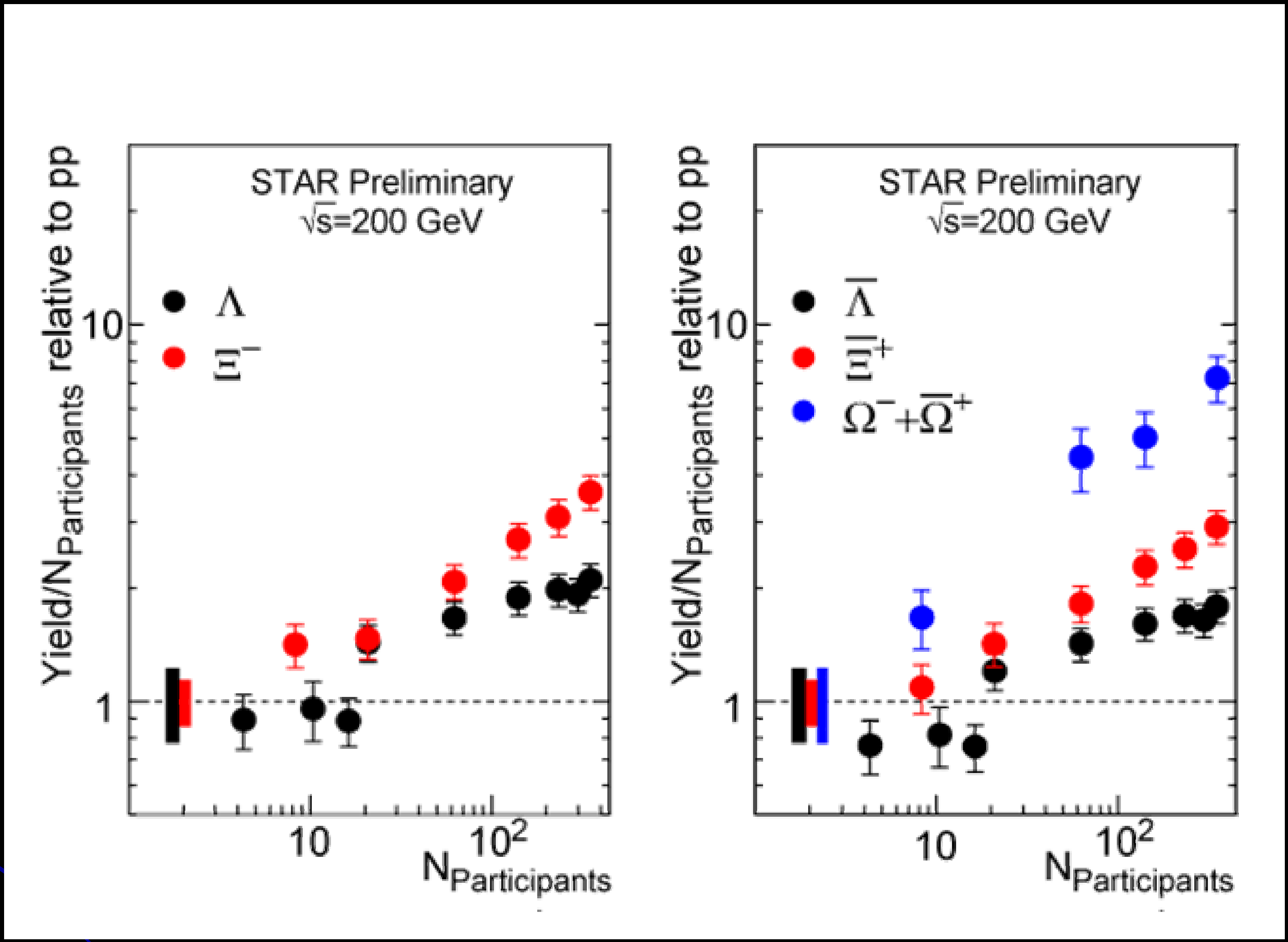
    just due to creation of particle itself. The rest of the system acts as a reservoir and "picks up the slack"



- removal of canonical suppression
  - increases with strangeness
  - ~ observed enhancements
  - detailed centrality dependence not reproduced (very crude modelling)

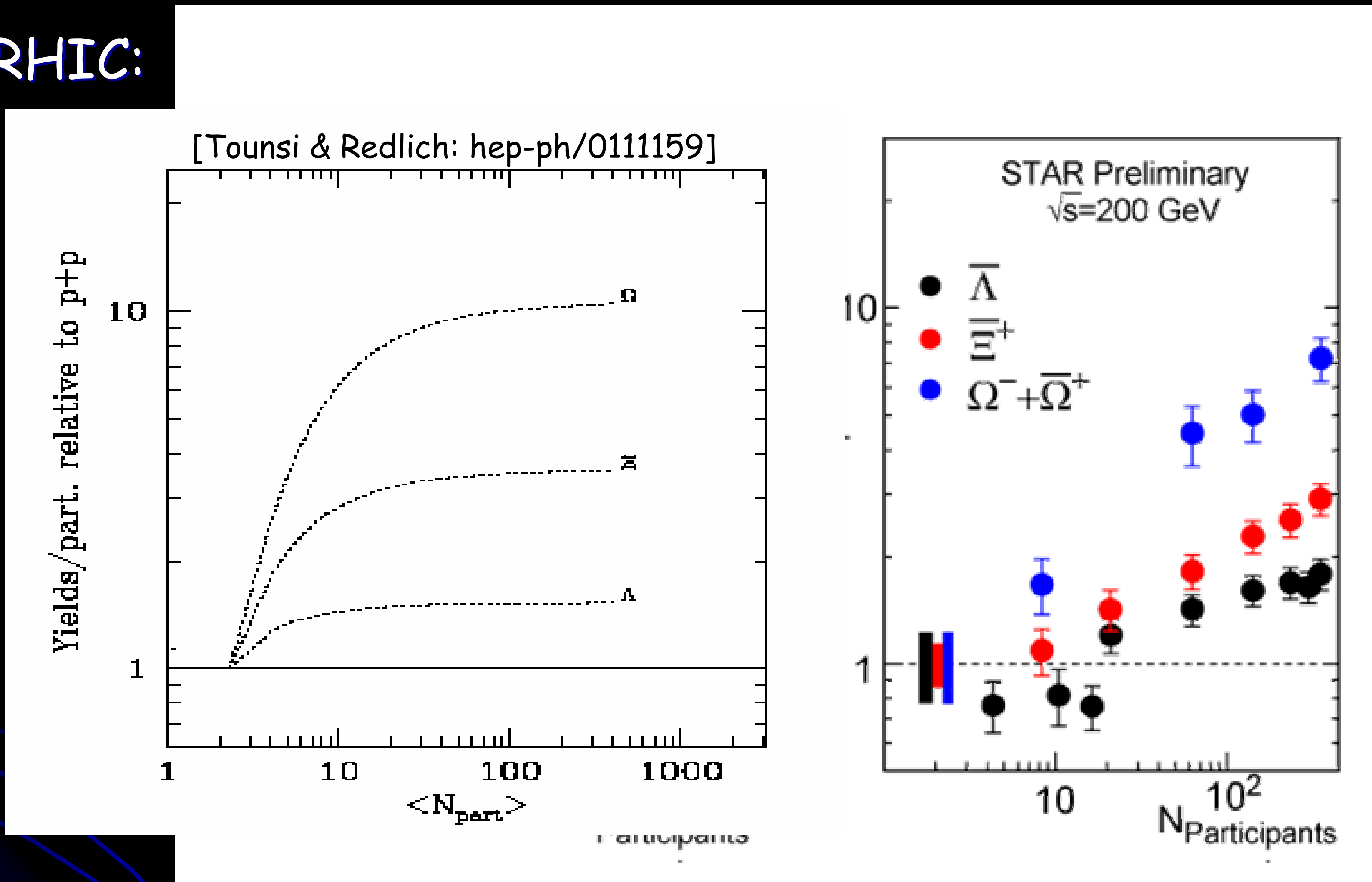
[Hamieh et al.: Phys. Lett. B486 (2000) 61]

- @ RHIC:



STAR Preliminary
√s=200 GeV
Λ
Ξ⁻
Yield/N_Participants relative to pp
N_Participants
10
1
10²
STAR Preliminary
√s=200 GeV
Λ̄
Ξ̄⁺
Ω⁻+Ω̄⁺
Yield/N_Participants relative to pp
N_Participants

- @ RHIC:



- decrease of enhancements from SPS predicted
- order of magnitude of enhancements close
- again, model for V_{corr} vs N_{part} seems to be inadequate

Does this *explain* the observed enhancement pattern?

- a system <u>in eq.</u>, if it is large enough, is in GC eq., but being large in itself is not a sufficient condition for being GC!
  - if AA colls. were just a superposition of pp, they would have to be treated canonically all the same!

- the system must also know it is large…
  - it must know that an $\bar{\Omega}^{+}$ generated here can be compensated by, say, an Ω^{-} on the other side of the fireball!
  - what counts is the *correlation volume*

- "Canonical Suppression is removed!"
  - an *observation*, not an *explanation*

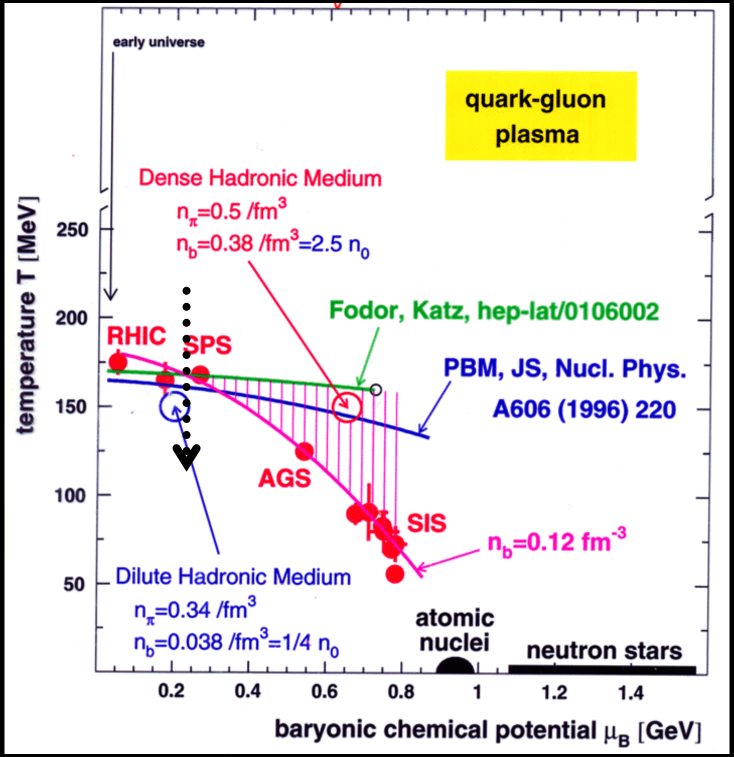
How is Canonical Suppression removed?

how does the system know it is large?

how can information travel so quickly through the system?

→ not by conventional hadronic transport (no time!)

- natural if the system is coming back from deconfinement



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- two recent ideas:
  - quantum coherence in the fireball [Stock: hep-ph/0312039]
    - can it be developed into testable model?
    - what about pA?
  - multi-particle interactions [Braun-Munzinger et al.: nucl-th/0311005]
    - only important close to phase boundary
    - if true, we are actually *measuring* Tc
    - microscopic mechanism to restore abundances to hadronic eq.

An equilibrium *pre*-diction

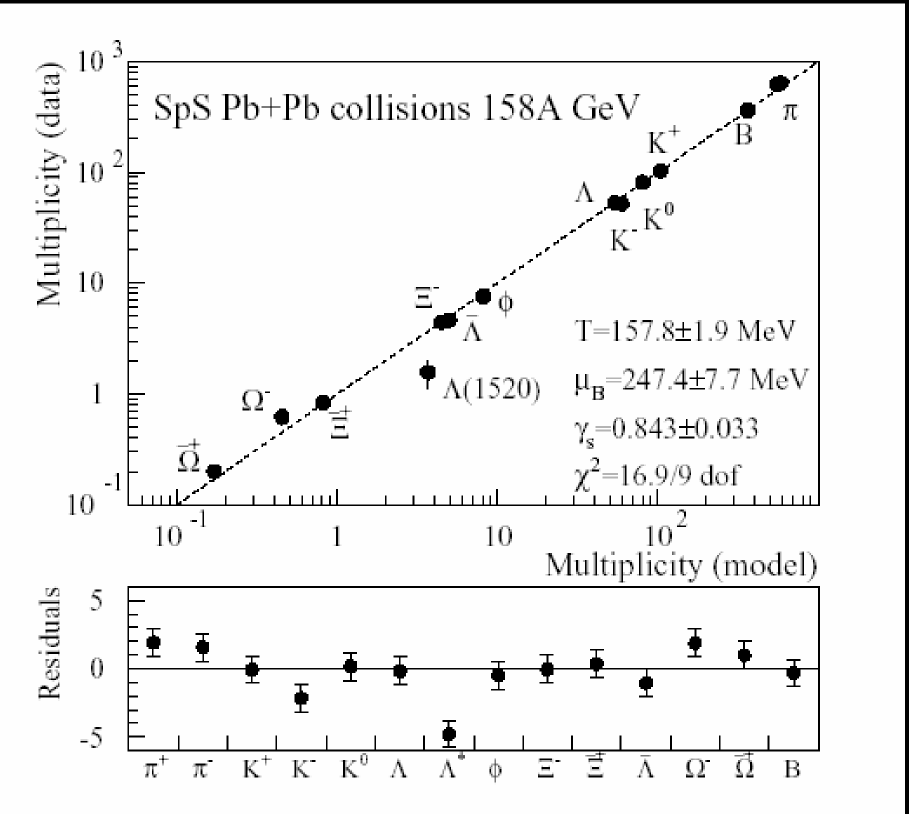
- mid-rapidity multi-strange/Λ @ 40 GeV SPS
  NA57 vs [Becattini: private communication]
  - γ_s = 1, T from 4π fit to NA49 40 GeV [Becattini et al.: hep-ph/0310049]
    - using $\pi^{\pm}$, $K^{\pm}$, φ, Λ and $\overline{\Lambda}$
  - Λ and $\overline{\Lambda}$ dN/dy from NA57 fix μ_B and normalization
  - Prediction of Ξ^- $\overline{\Xi}^+$ Ω^- and $\overline{\Omega}^+$ dN/dy
    - total χ^2/dof = 1.4 against values measured by NA57

  → No parameter for multi-strange
  again, not bad...

Physics beyond equilibrium?

→ look at fine details

Λ(1520)



Fit to NA49 data
[Becattini et al.: hep-ph/0310049]

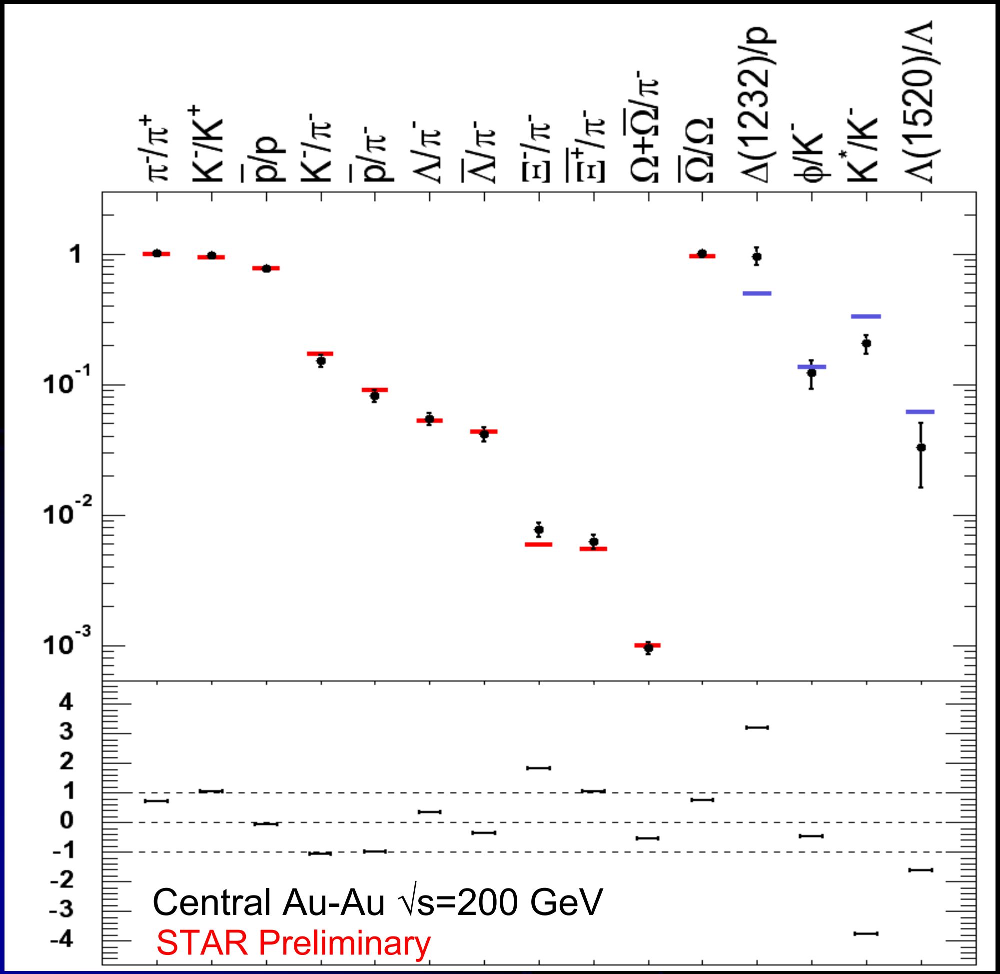
- Λ(1520) deviates from sistematics (~ 1/2)
  e.g.: [Markert: J. Phys. G 28 (2002) 1753]

→ we look for in-medium effects

we take fits very seriously!

Resonances @ RHIC

- new: Λ(1520), K*(892), Δ(1232) in STAR at 200 GeV



- resonances show larger deviations from statistical fit
- rescattering vs regeneration?
  - see talk by P. Fachini

Non equilibrium: γ_s

- 4π yield ratios sometimes preferred for thermal fits
  - to be safe in case strangeness ends up too far away in rapidity from where originally produced
  - (but can one assume global equilibrium with same T and <u>same μ_B</u> at different rapidities?)

- in this case $\gamma_s \sim 0.7 - 0.8$ must be introduced
  - strangeness undersaturation factor:

    for each particle, a factor $\gamma_s^{N(s+\bar{s})}$

    e.g.: [Becattini et al.: hep-ph/0310049]
  - could it also mimic residual canonical suppression?

Non equilibrium: γ_s & γ_q

see e.g.: [Rafelski & Letessier: hep-ph/0309030]

- γ_q controls overall abundance of $q\bar{q}$
- old γ_s becomes γ_s/γ_q
- w.r.t. previous, additional factor $\gamma_q{}^B$ for baryons
- fits get beautiful e.g.: @ RHIC →
  [see also Becattini et al.: hep-ph/0310049]
  (but additional parameter)
- @ RHIC 130:
  $\gamma_q = 1.6 \pm 0.2$ $\gamma_s/\gamma_q = 1.3 \pm 0.1$

ratio	RHIC-130	non-eq fit	χ^2
π^+/p	9.5 ± 1.4	9.07	1.15
$\pi^-/\bar{p}$	13.4 ± 0.9	13.15	0.08
$\bar{p}/h^-$	–	0.0459	–
Λ_c/h^-	0.059 ± 0.004	0.0509	4.11
$\overline{\Lambda_c}/h^-$	0.042 ± 0.004	0.0379	1.04
Ξ_c^-/h^-	0.0079 ± 0.0012	0.00805	0.01
$\overline{\Xi_c^-}/h^-$	0.0066 ± 0.001	0.00645	0.02
Ω/h^-	$(12 \pm 5)10^{-4}$	$13.2\,10^{-4}$	0.06
$(\overline{\Omega}+\Omega)/h^-$	$(22 \pm 6.5)10^{-4}$	$24.8\,10^{-4}$	0.19
Λ_c/p	0.90 ± 0.12	0.747	1.63
$\overline{\Lambda_c}/\bar{p}$	0.93 ± 0.19	0.826	0.30
Ξ^-/Λ	0.193 ± 0.03	0.189	0.02
$\overline{\Xi^-}/\overline{\Lambda}$	0.219 ± 0.035	0.207	0.12
Ω/Ξ^-	–	0.164	–
$\overline{\Omega}/\overline{\Xi^-}$	–	0.180	–
$(\overline{\Omega}+\Omega)/(\overline{\Xi}+\Xi)$	0.150 ± 0.04	0.171	0.28
$\bar{p}/p$	0.71 ± 0.06	0.674	0.36
$\overline{\Lambda_c}/\Lambda_c$	0.71 ± 0.04	0.745	0.78
$\overline{\Xi}/\Xi$	0.83 ± 0.08	0.801	0.13
$\overline{\Omega}/\Omega$	0.95 ± 0.1	0.878	0.51
K^+/π^+	0.17 ± 0.02	0.195	1.59
K^-/π^-	0.15 ± 0.02	0.180	2.28
K^-/K^+	0.87 ± 0.07	0.923	0.57
K^{*0}/K^-	0.26 ± 0.08	0.231	0.13
ϕ/h^-	0.02 ± 0.002	0.0212	0.37
ϕ/K^-	0.15 ± 0.03	0.148	0.00
ϕ/K^{*0}	0.595 ± 0.24	0.639	0.03

$\sqrt{s_{NN}}$ [GeV]	200	130	200	130
T [MeV]	143 ± 7	144 ± 3	160 ± 8	160 ± 4
μ_b [MeV]	21.5 ± 31	29.2 ± 4.5	24.5 ± 3	31.4 ± 4.5
μ_s [MeV]	2.5 ± 0.2	3.1 ± 0.2	2.9 ± 0.2	3.6 ± 0.2
μ_S [MeV]	4.7 ± 0.4	6.6 ± 0.4	5.3 ± 0.4	6.9 ± 0.4
γ_q	$1.6 \pm 0.3^*$	$1.6 \pm 0.2^*$	1^*	1^*
γ_s/γ_q	1.2 ± 0.15	1.3 ± 0.1	1.0 ± 0.1	1.13 ± 0.06
χ^2/dof	2.9/6	15.8/24	4.5/7	32.2/25
$P_{\rm true}$	90%+	95%+	65%	15%

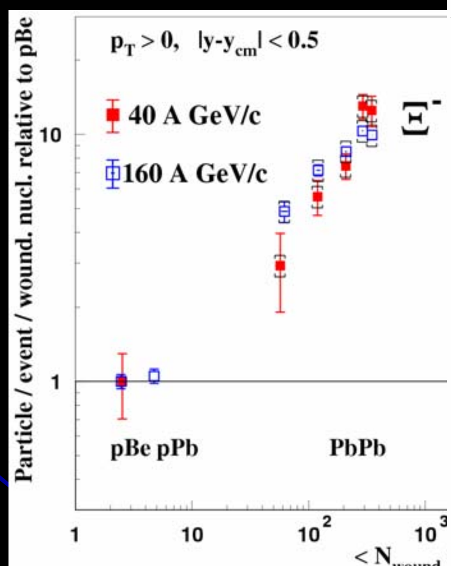
- strangeness actually enhanced <u>above hadronic equilibrium values</u>?

- pentaquark production (if statistical) would be particularly sensitive to need for γ_q!
  - additional $\gamma_q{}^2$ factor for Θ^+ w.r.t. other models

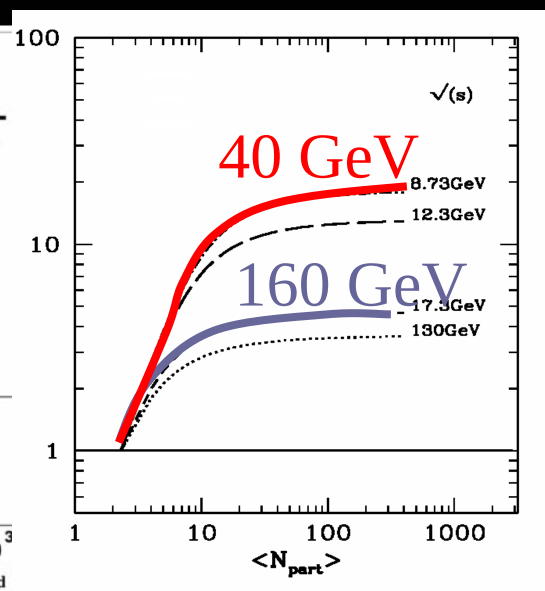
e.g.: [Letessier et al.: hep-ph/0310188, Becattini et al.: hep-ph/0310049]

Hyperon enhancements at 40 GeV

- enhancements vs N_{wound} steeper at 40 than at 160
- C to GC predicts a factor 4 - 5 larger Ξ^- enhancement at 40 GeV than at 160, not seen in the data



[Bruno (NA57): yesterday]

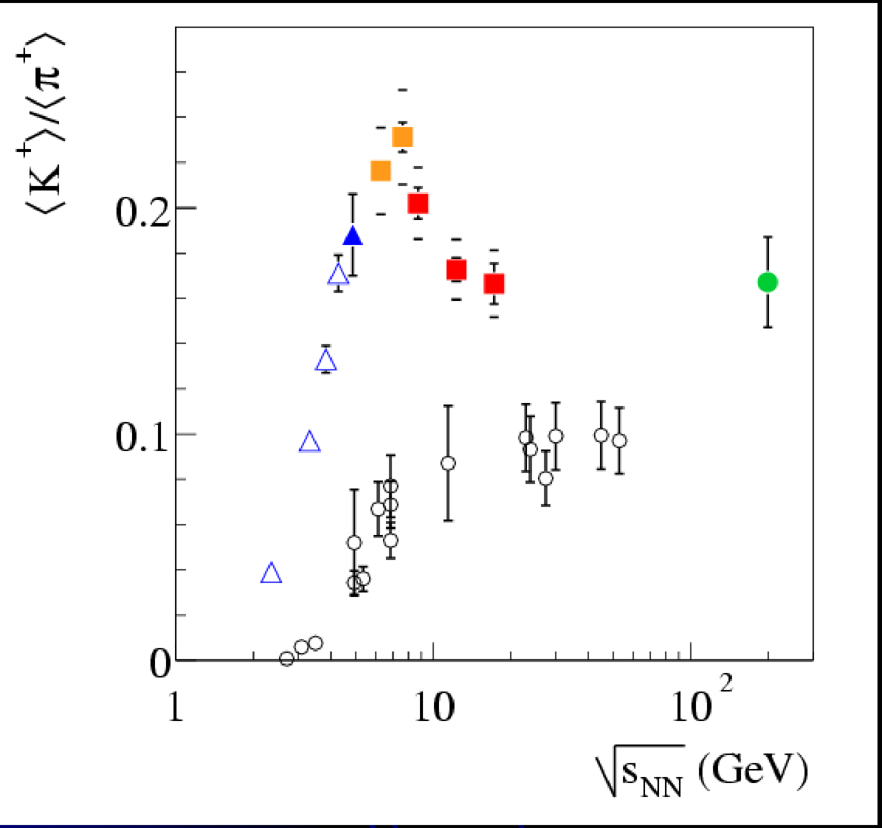


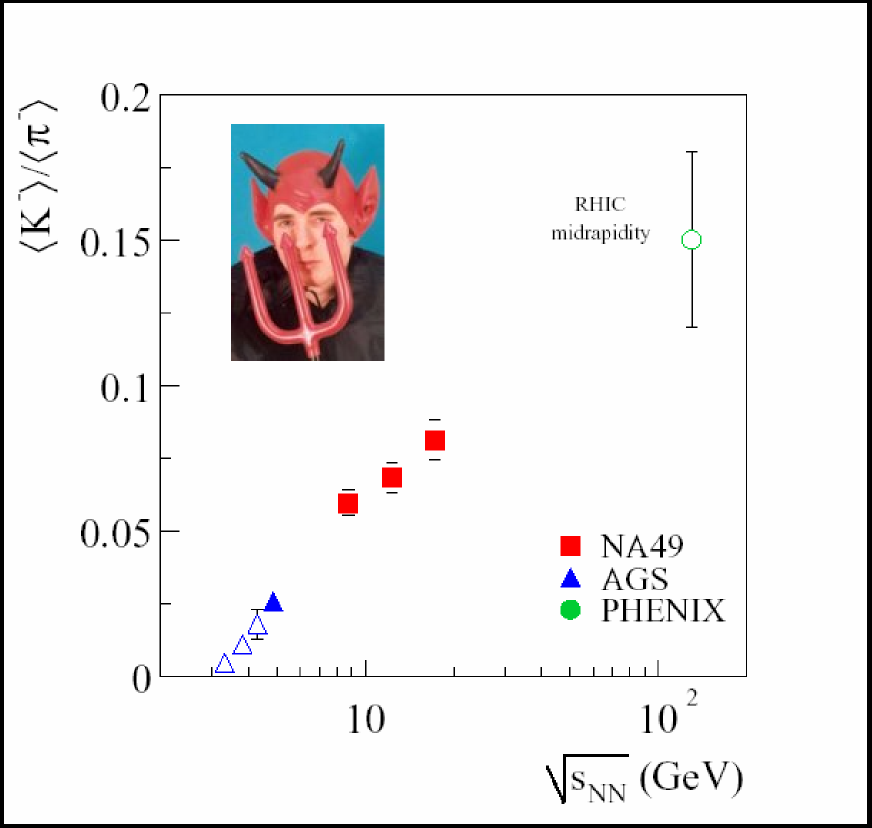
[Tounsi & Redlich: hep-ph/0111159]

- perhaps yields trying to shoot up but don't go all the way?
  - on the other hand, equilibrium fit not too bad... [Becattini: priv. comm]

Marek's Horn

- Change of behaviour of K^+/π^+ in A-A around 30 GeV
  - K^-/π^- has a smooth behaviour with energy

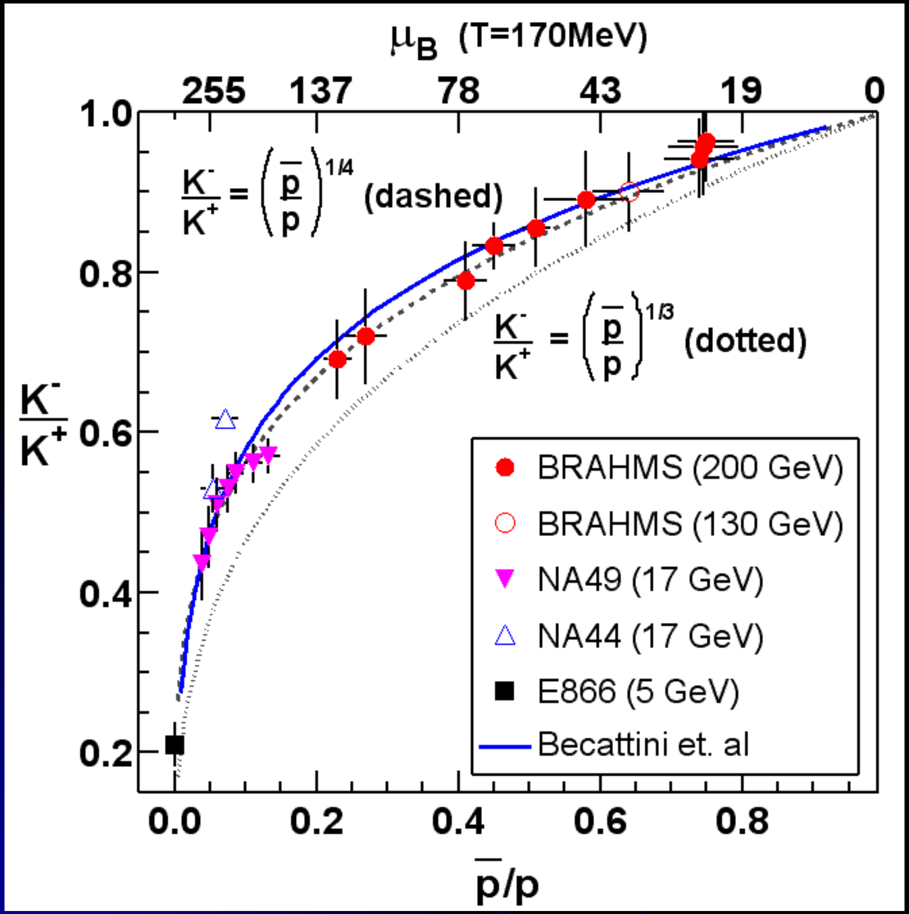


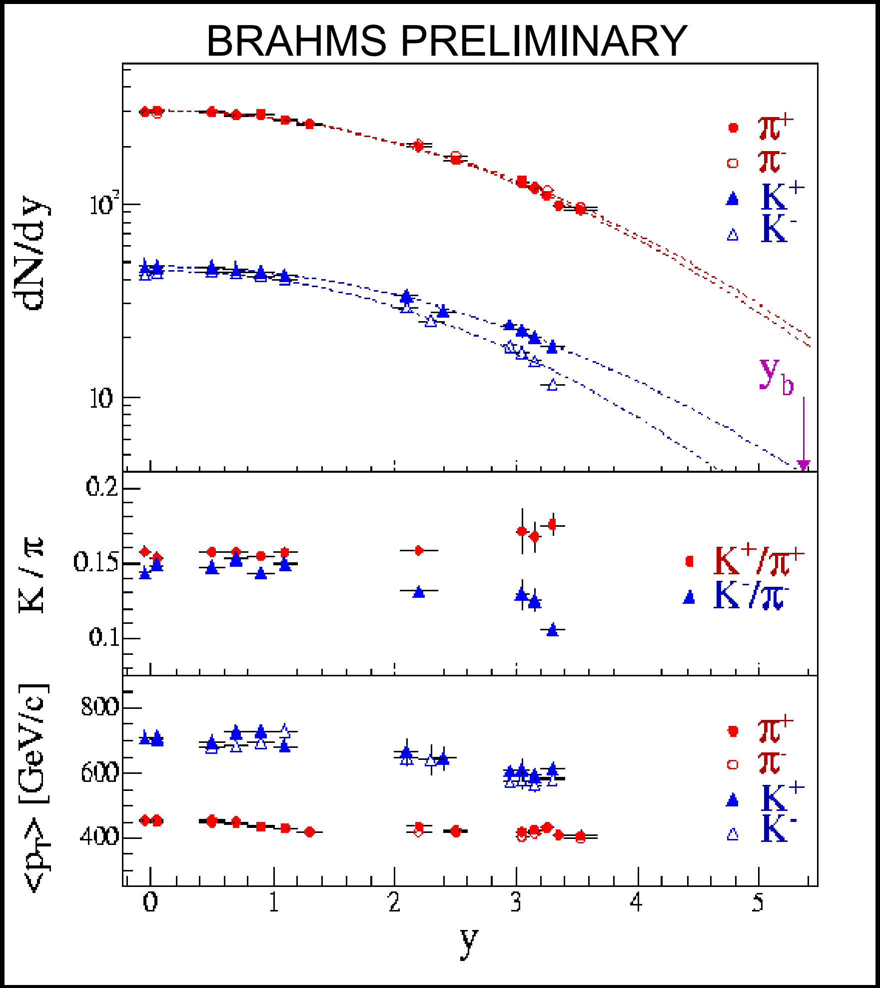


- Could this signal chiral transition?

Brahms: K± vs y

- caution! K± sensitive to baryon density...

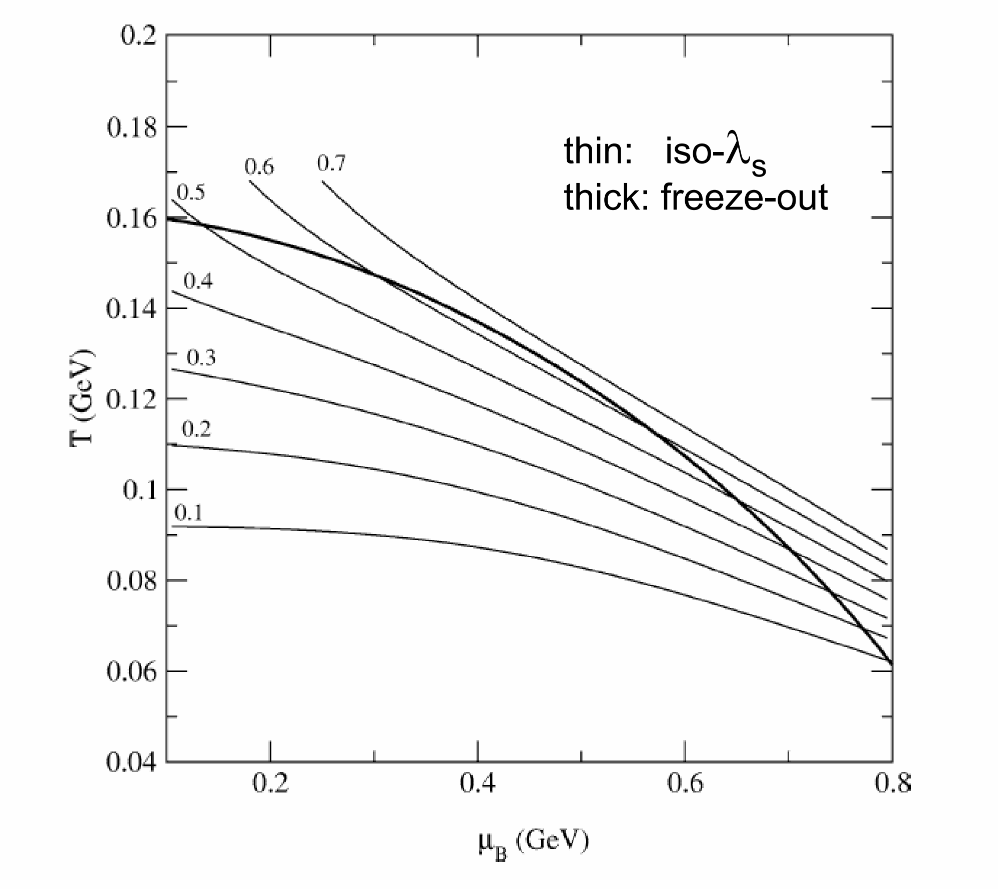




[Brahms: Phys. Rev. Lett. 90 (2003) 102301]

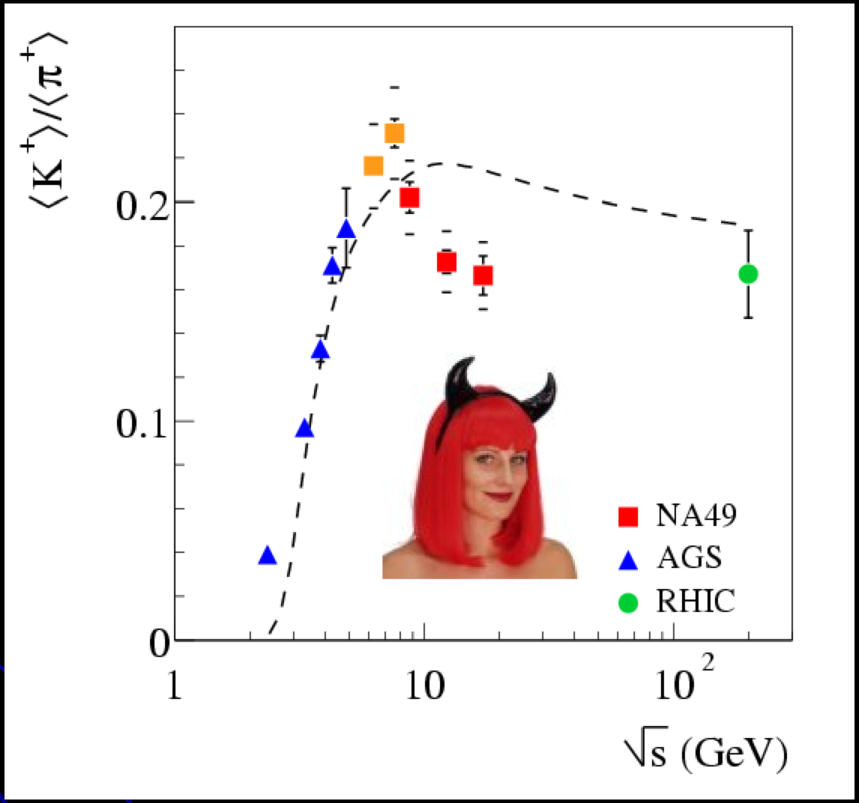
[D. Ouerdane, PhD Dissertation, Copenhagen University, Aug. 03]

- ... and λ_s [$= 2\langle s\bar{s}\rangle / (\langle u\bar{u}\rangle + \langle d\bar{d}\rangle)$] max. around 30 GeV:



[Braun-Munzinger et al.: NPA697(2002)902]

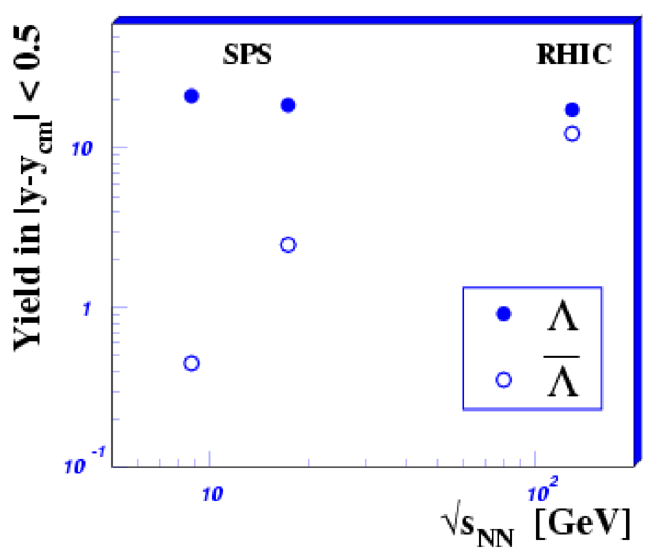
- so one expects a broad maximum in K^+/π^+ about there...

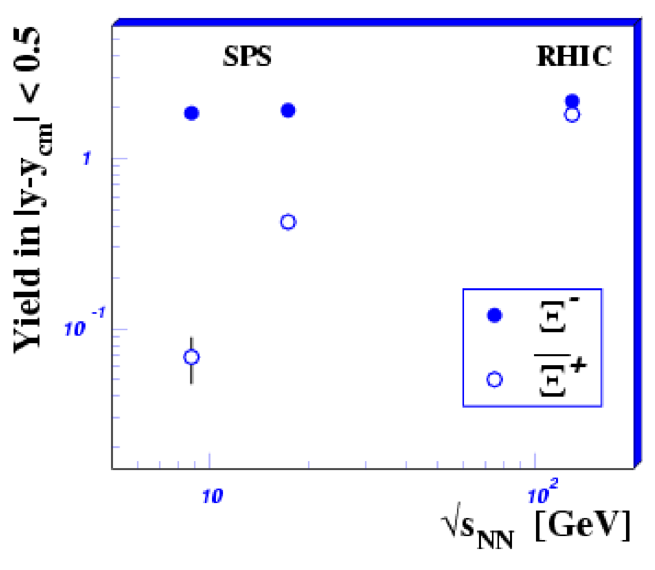


- but nothing so sharp!
  - → it looks like we have some anomaly...

Absolute values of hyperon dN/dy

see talk by D.Elia, Friday, P2

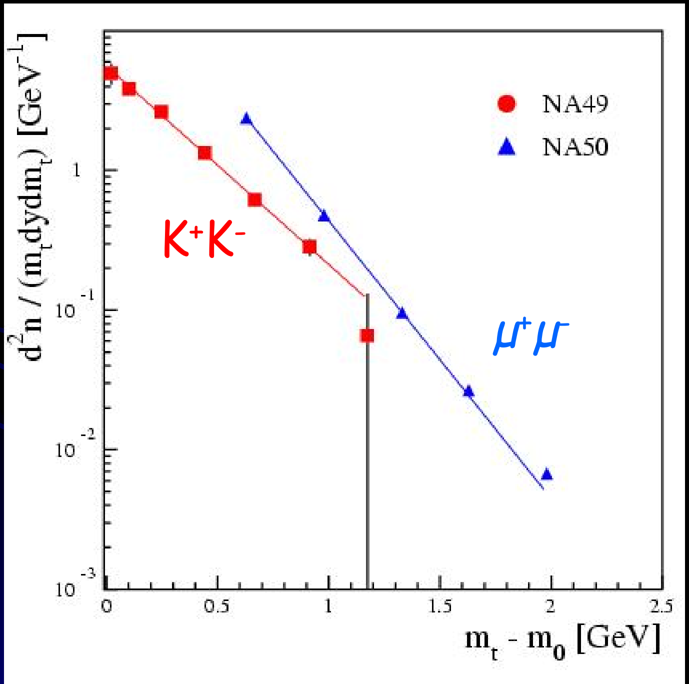




- absolute values of $\overline{\Lambda}$ and $\overline{\Xi}^{+}$ dN/dy go up with $\sqrt{s}$...
- absolute values of Λ and Ξ^{-} dN/dy ~ constant from $\sqrt{s_{NN}}$ = 8.8 to 130 GeV !
- Statistical fits: T and μ_B only sensitive to particle ratios
  - overall normalization of yields controlled by fitted V parameter
- T, μ_B and V all vary with energy, but in such a way as to ensure Λ, Ξ^{-} yields stays constant ...
  - there must be a simple reason ...

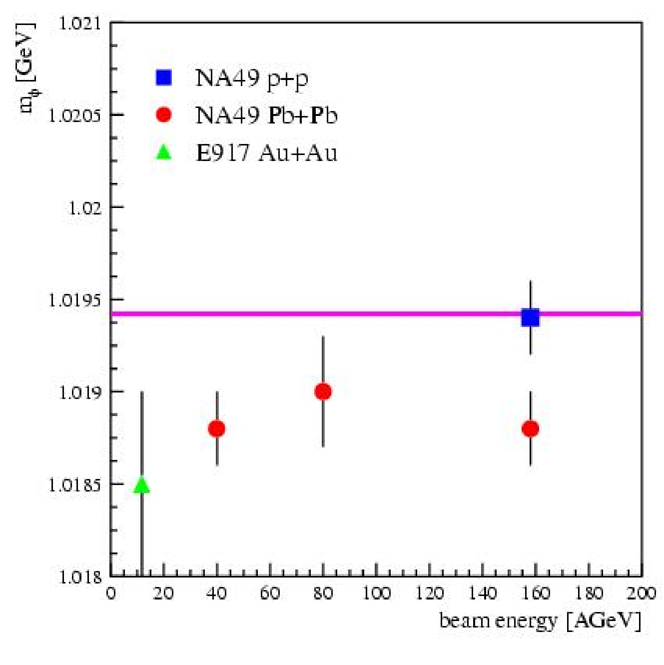
The mysterious Φ

- Φ fundamental to understand γ_s vs C suppression
  - γ_s^2, but no C suppression
- the NA49 – NA50 discrepancy is still with us…



→ NA60 should provide high stats, low p_T $\Phi \rightarrow \mu\mu$

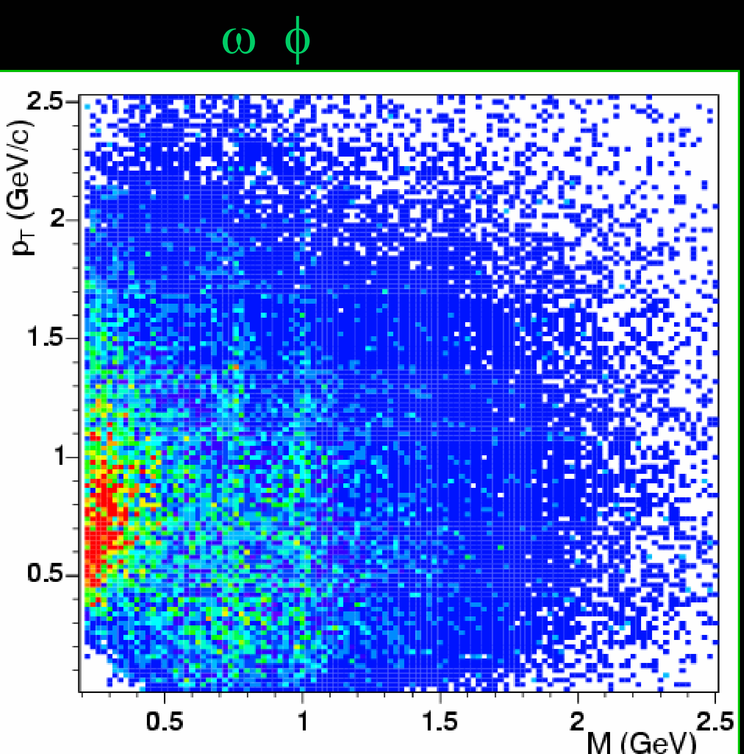
- NA49: small deviation from PDG mass seen in all three Pb+Pb data sets, but not in pp

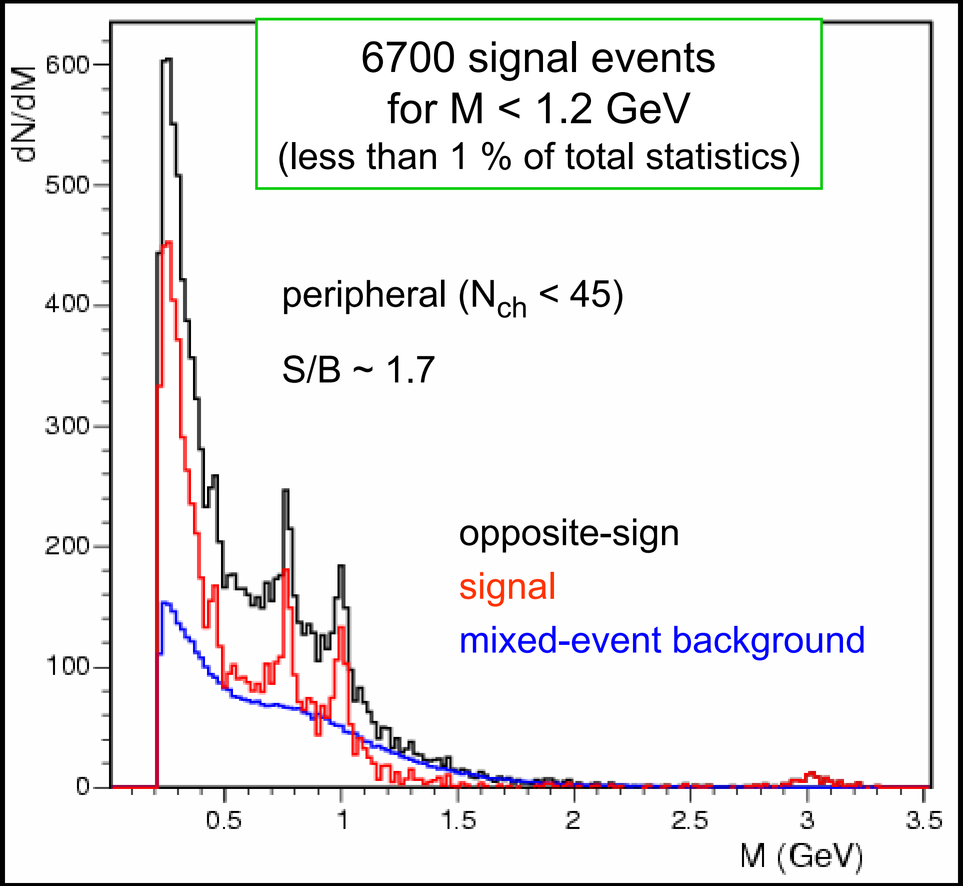


see [NA49 (Friese): SQM 03]

First Φ signal from NA60

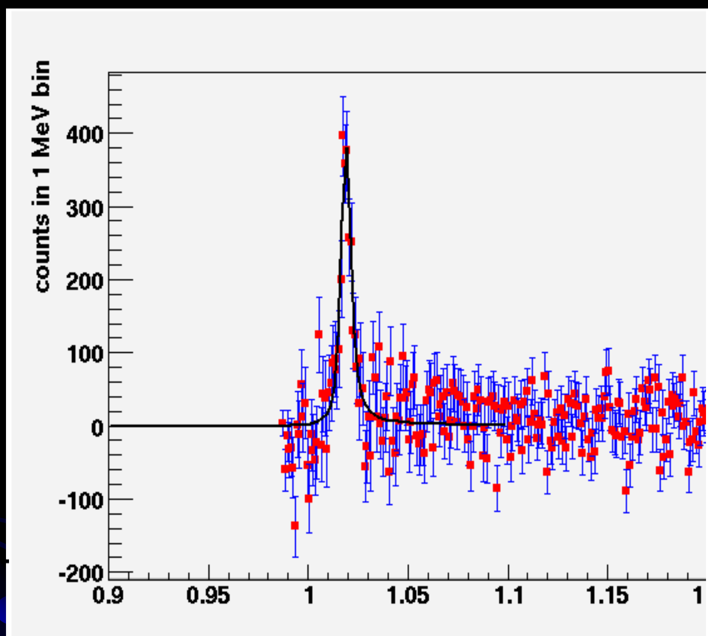
- peripheral In-In
- expected > 100k Φ → $\mu^+\mu^-$
- expected mass resolution: ~ 20 MeV
- also looking at Φ → K^+K^-



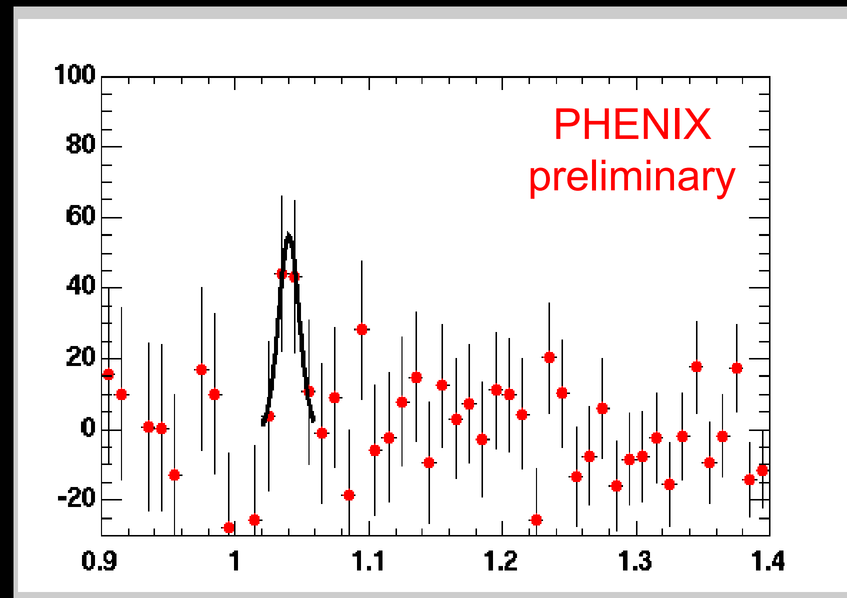


Φenix

- Φ → K^+K^- (min bias 200 GeV)



- Φ → e^+e^- (min bias 200 GeV)



- Mass and width agree within errors with PDG values

- <u>Preliminary yields</u>:

$$\phi \to e^+e^- : \quad \frac{dN}{dy} = 5.4 \pm 2.5\,(stat)^{+3.4}_{-2.8}\,(sys)$$

$$\phi \to K^+K^- : \quad \frac{dN}{dy} = 2.01 \pm 0.22\,(stat)^{+1.01}_{-0.52}\,(sys)$$

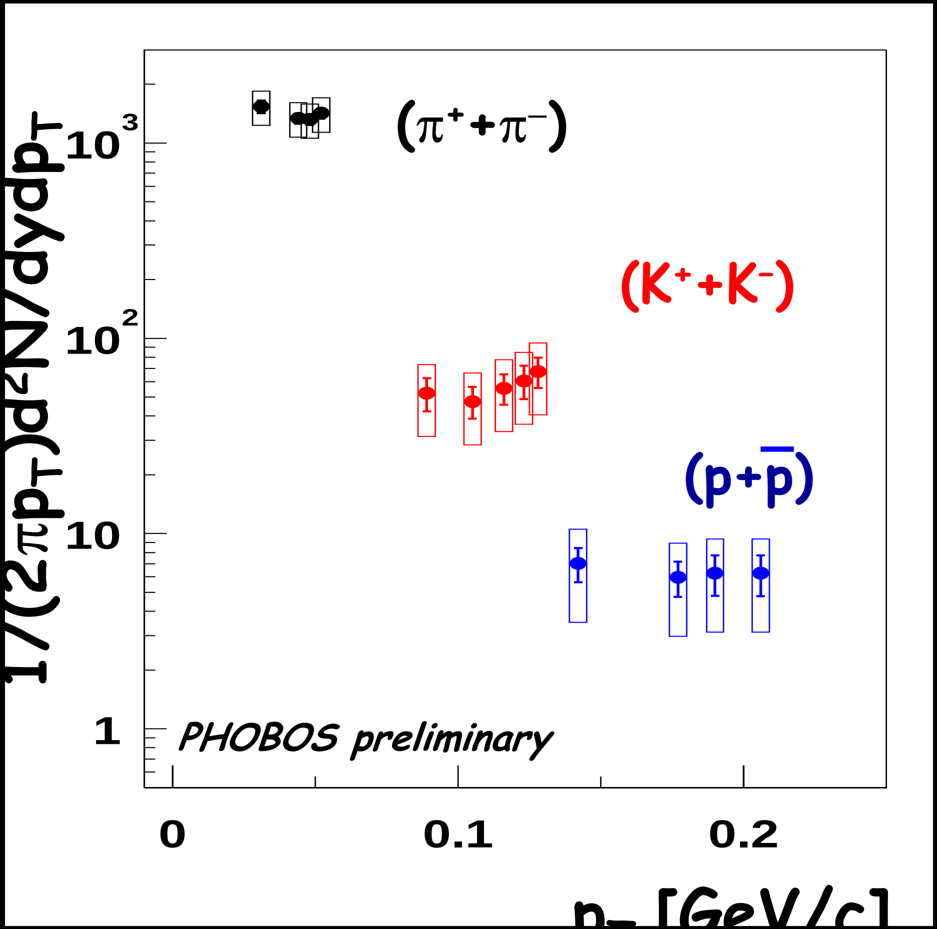
see [Phenix (Maguire): SQM 03]

Extras…

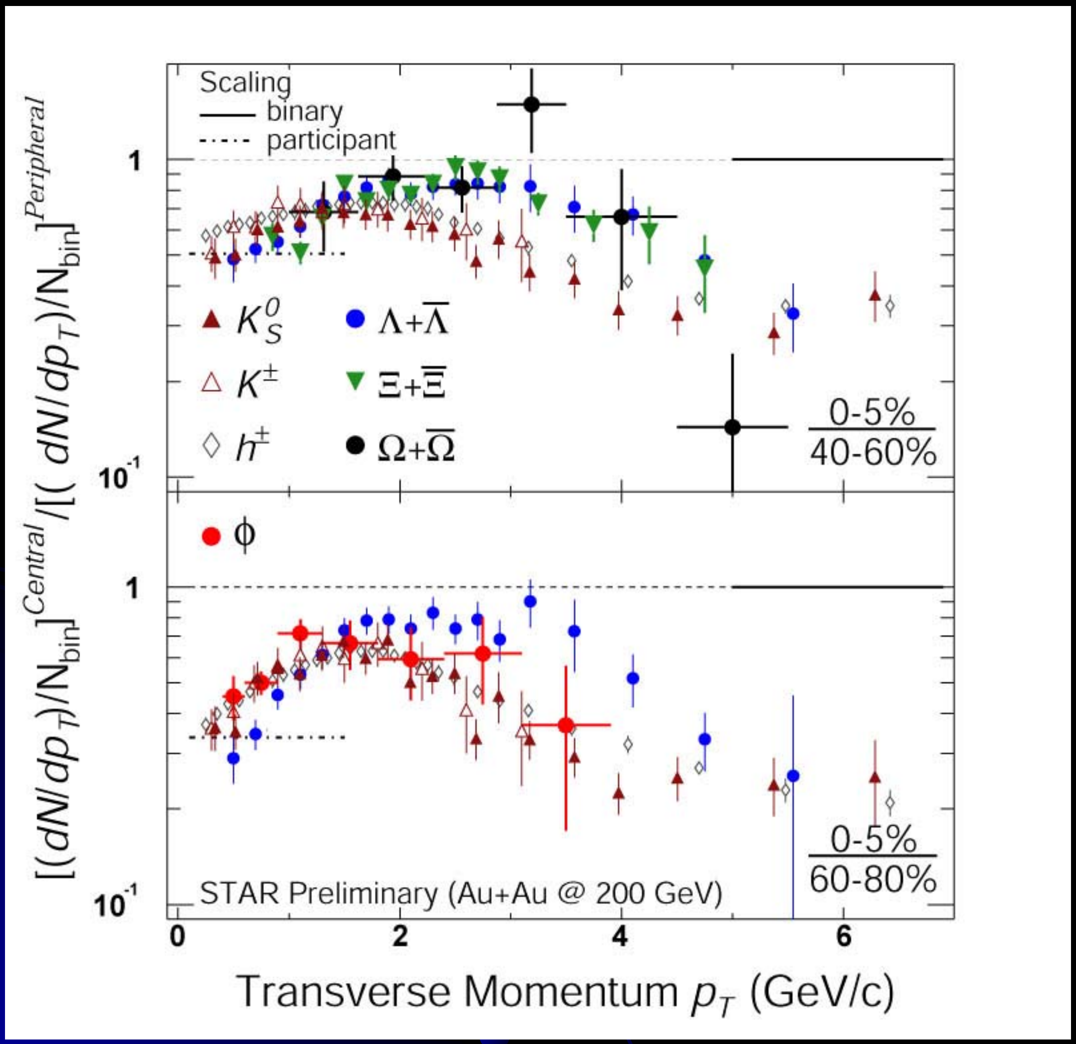
some results on spectra that I could not resist showing…

Very low p_T π, K, p from Phobos !

- tracks characterized by range and energy loss in Si layers
  - → particle id.
  - → momentum within 5%
- unique constraints for transport, hydro, thermal models

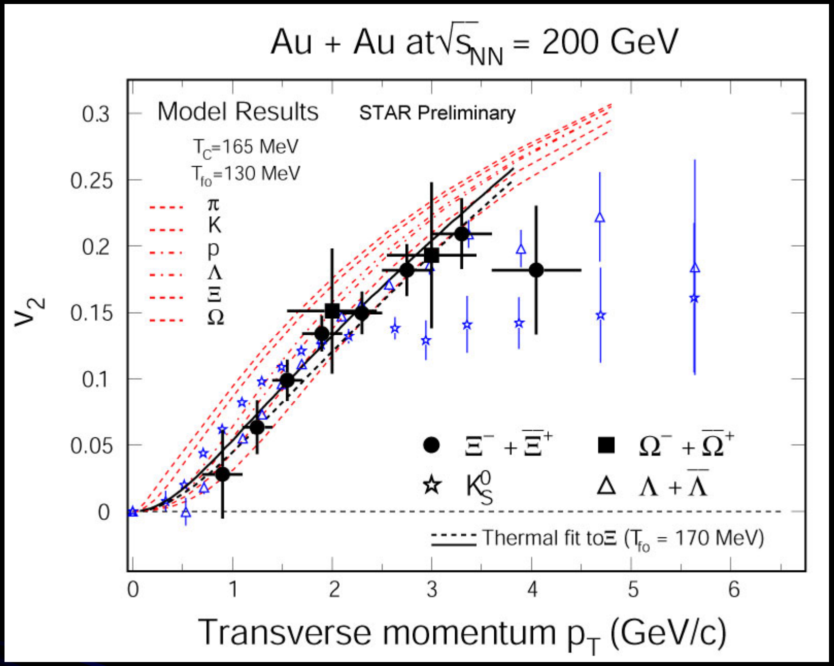


Rcp for multistrange !

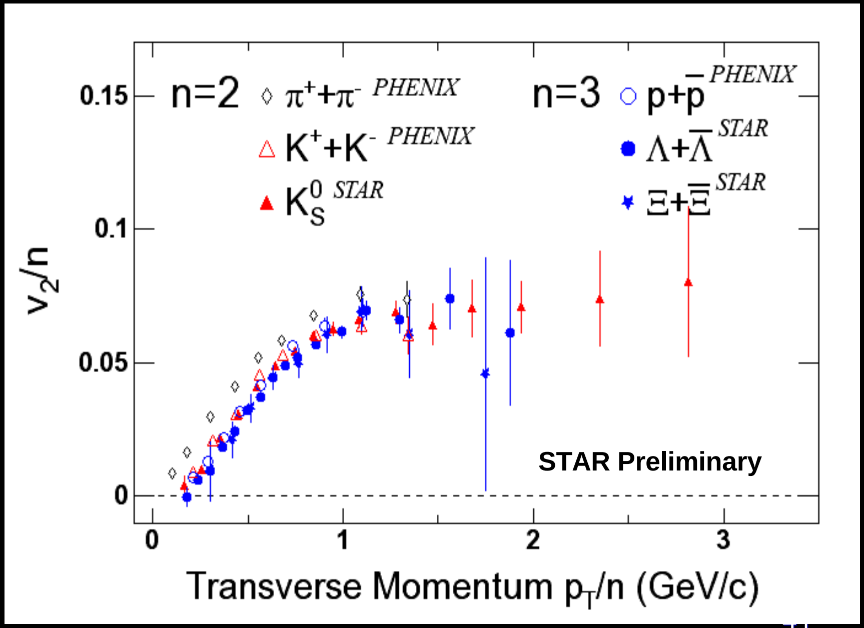


- Φ seems to follow K^0_s more than Λ
  - → meson-baryon, not mass?

v2 for multistrange !

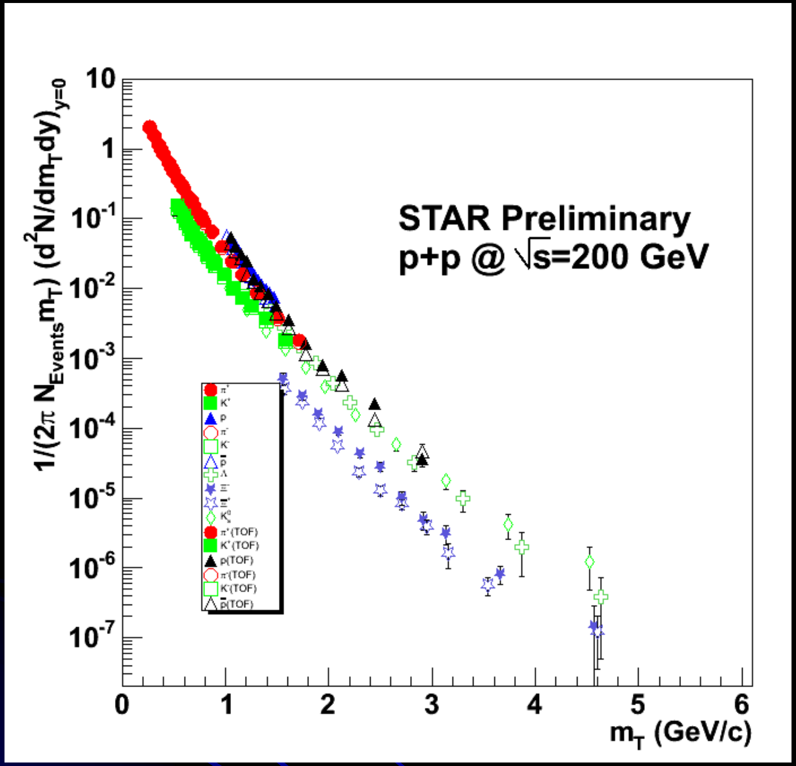


scaled with n(quarks)



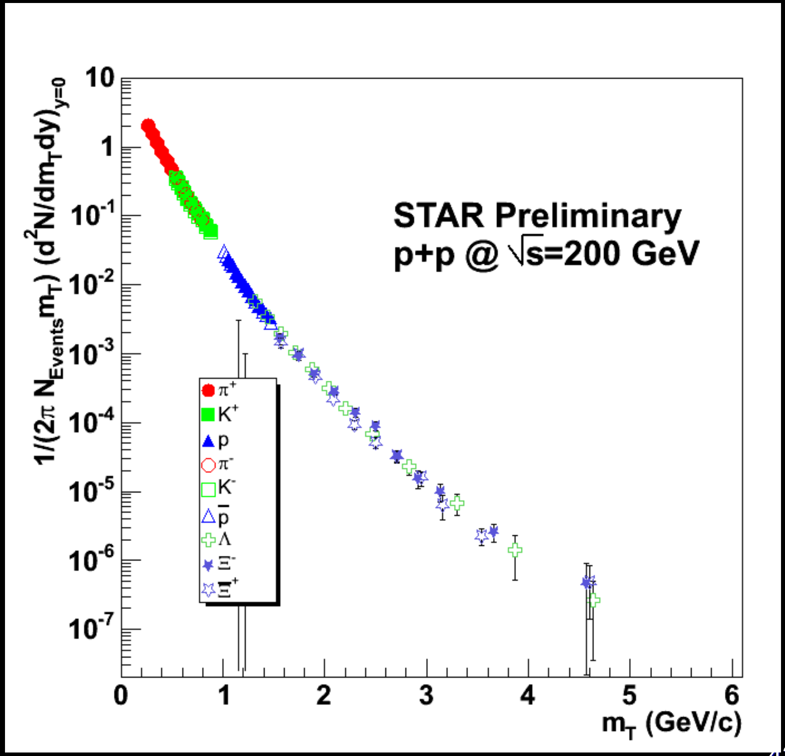
- scaling seems to work
  (not for pions…)
  → parton recombination?

m_T scaling in pp...



not absolute...

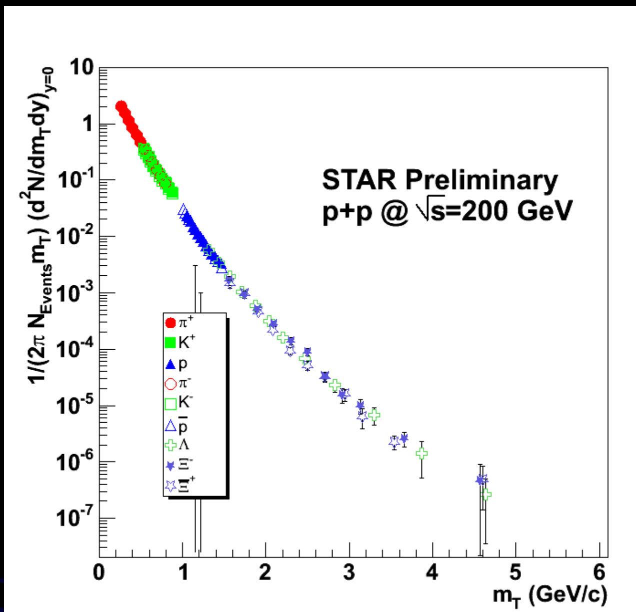
...but if one rescales:

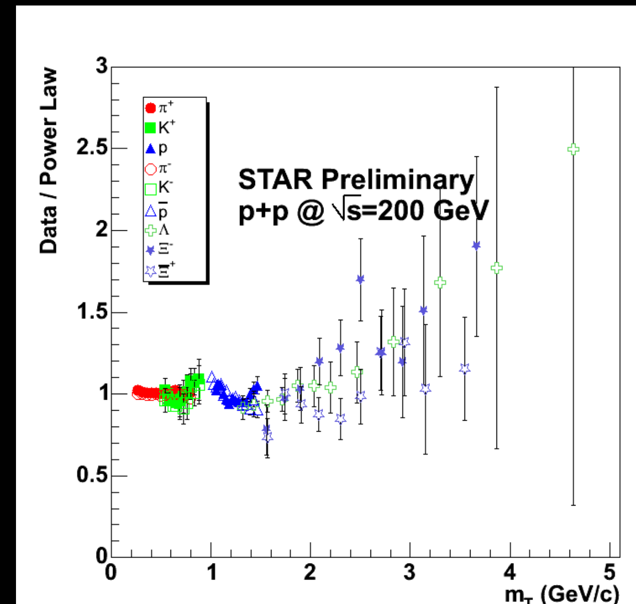


… but not in Au-Au

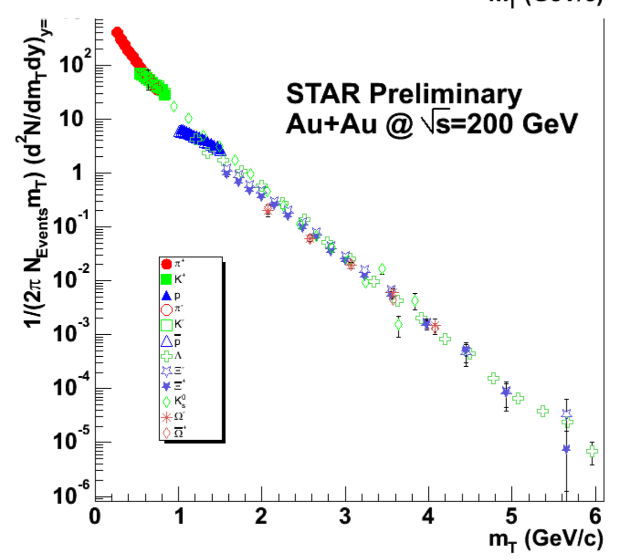
data

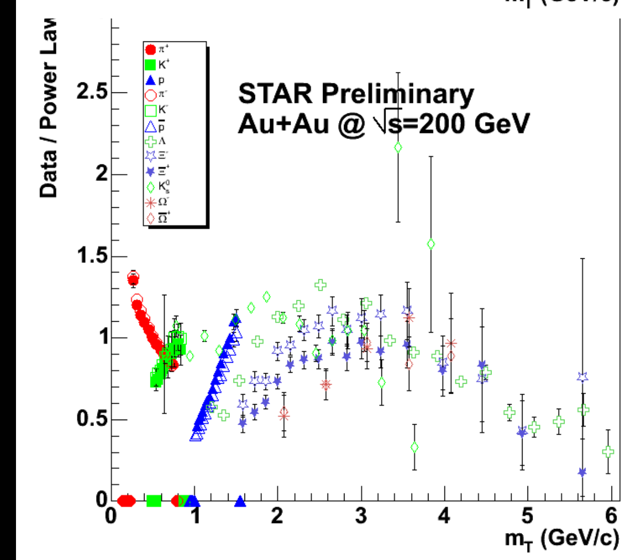
data / power law





← p-p →



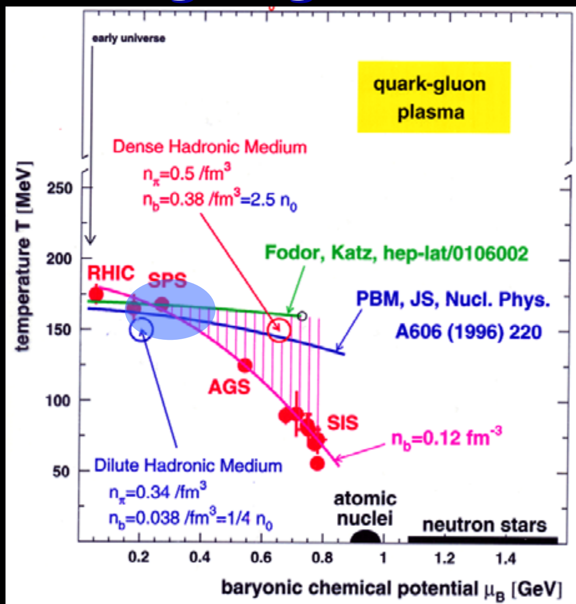


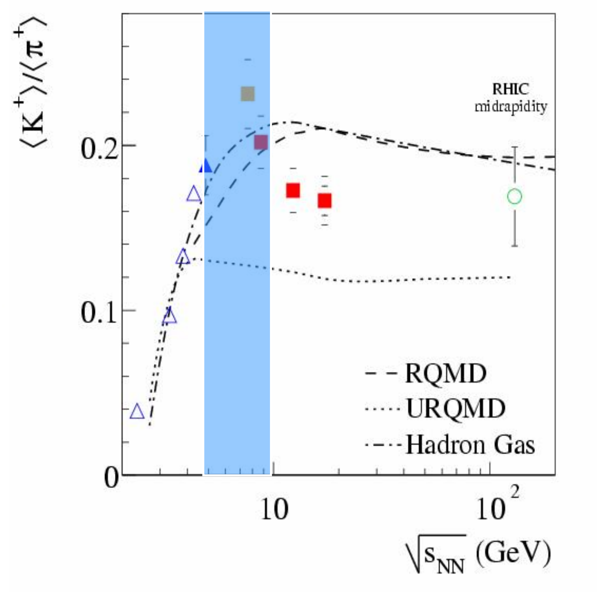
← Au-Au →

Conclusions

- Evidence for high degree of chemical equilibration
  - even for rare, multistrange particles
  - → QGP prediction !
  - → freeze-out curve traces expected phase boundary at SPS - RHIC
  - → hadronic transport does not seem to be able to do it (no time!)
- RHIC opening up exciting new windows for strangeness !
  - elliptic flow, high p_T, high statistics reference data (pp, dAu)
- Strangeness perhaps enhanced above hadronic equilibrium !
  - stand-alone smoking gun?

- we must understand (non-)equilibrium
  - we need highest possible precision data on yields and ratios (RHIC!)
  - (we need theory to provide agreed statistical approach)
  - we need to understand the Φ
    - precision data from NA60 and Phenix
- we must understand what's going on in the region $\sqrt{s_{NN}}$ = 5 - 10 GeV
  - low E SPS ?
  - SIS 200 @ GSI !





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